

APPENDIX F

INTRINSIC REMEDIATION DEMONSTRATION AT PATRICK AFB, FLORIDA

**FINAL
INTRINSIC REMEDIATION
TREATIBILITY STUDY**

for

**SITE ST-29
PATRICK AIR FORCE BASE
FLORIDA**

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Prepared for:

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EXECUTIVE SUMMARY

This report presents the results of a treatability study (TS) performed by Parsons Engineering Science, Inc. (Parsons ES) at Patrick Air Force Base, Florida to evaluate the use of intrinsic remediation with long-term monitoring (LTM) as a remedial option for dissolved benzene, toluene, ethylbenzene, and xylene (BTEX) contamination in the shallow saturated zone near the BX Service Station (Site ST-29). Soil and groundwater contamination caused by motor vehicle gasoline is known to occur at the site, with contamination being present in the aqueous and gaseous phases and as residual light nonaqueous-phase liquid (LNAPL) within the aquifer matrix. There is no evidence of mobile LNAPL (free product) at this site. This study focused on the impact of the dissolved BTEX and residual LNAPL on the shallow groundwater system at the site. Site history and the results of previous soil and groundwater investigations also are summarized in this report. To ensure compliance with Chapter 62770.600(8) of the Florida Administrative Code (FAC), future groundwater sampling at the site should include an analysis of all compounds specific to underground storage tank releases identified under this code (as listed in Table 6.1).

An important component of this study was an assessment of the potential for contamination in groundwater to migrate from Site ST-29 to potential exposure points. The Bioplume II solute fate and transport model was used to estimate the rate and direction of dissolved BTEX movement through the shallow saturated zone under the influence of advection, dispersion, sorption, and biodegradation. Input parameters for the Bioplume II model were obtained from existing site characterization data, supplemented with data collected by Parsons ES in conjunction with personnel from the United States Environmental Protection Agency (USEPA) Robert S. Kerr Environmental Research Laboratory. Model parameters that were not measured at the site were estimated using reasonable literature values for materials similar to those found at the site.

The results of this study suggest that dissolved BTEX contamination present in groundwater poses no significant threat to human health or the environment at its present, or predicted future, concentration and distribution under current land use conditions. The Air Force therefore proposes to implement intrinsic remediation with LTM for dissolved BTEX contamination in groundwater at this site. To reduce sources of continuing contamination, the Air Force also proposes to continue bioventing activities currently taking place at the site.

To verify the Bioplume II model predictions, the Air Force proposes to use six LTM wells/points and three point-of-compliance (POC) monitoring wells to monitor the long-term migration and degradation of the dissolved BTEX plume. Regular sampling and analysis of groundwater from these sampling points will allow the effectiveness of intrinsic remediation to be monitored and should allow sufficient time to implement hydraulic controls to contain the plume if BTEX compounds are detected at levels of regulatory concern in the POC wells. These wells should be sampled on a semiannual basis for at least 10 years. If the data collected during this period support the anticipated effectiveness of intrinsic remediation, the sampling frequency can be reduced to once every year for 5 years. If chemical concentrations in groundwater from the POC wells exceed the Florida regulatory standards [per 62770.600(8), FAC] of 1 microgram per liter ($\mu\text{g/L}$) for benzene, 50 $\mu\text{g/L}$ for total BTEX, 3 $\mu\text{g/L}$ for 1,2-dichloroethane, 0.02 $\mu\text{g/L}$ for 1,2-dibromoethane, 50 $\mu\text{g/L}$ for lead, and 50 $\mu\text{g/L}$ for methyl tert-butyl ether, additional evaluation or corrective action may be necessary to remediate groundwater at the site.

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SECTION 1

INTRODUCTION

This report was prepared by Parsons Engineering Science, Inc. (Parsons ES) and presents the results of a treatability study (TS) conducted for the Air Force Center for Environmental Excellence (AFCEE) to evaluate the use of intrinsic remediation with long-term monitoring (LTM) for remediation of fuel-hydrocarbon-contaminated groundwater at the Base Exchange (BX) Service Station (Site ST-29), Patrick Air Force Base (AFB), Florida. Previous investigations determined that motor vehicle gasoline (MOGAS) had been released into the soil and shallow groundwater at the site. The main emphasis of the work described herein was to evaluate the potential for naturally occurring degradation mechanisms to reduce dissolved benzene, toluene, ethylbenzene, and xylene (BTEX) concentrations in groundwater to levels that are protective of human health and the environment. This demonstration is not intended to be a contamination assessment report or a remedial action plan; rather, it is provided for the use of the Base and its prime environmental contractors as information to be used for future decision making regarding this site.

As used throughout this report, the term "intrinsic remediation" refers to a management strategy that relies on natural attenuation mechanisms to control exposure of potential receptors to concentrations of BTEX in the subsurface that exceed regulatory levels of concern. "Natural attenuation" refers to the actual processes (e.g., sorption, dispersion, and biodegradation) that facilitate intrinsic remediation.

Intrinsic remediation is an innovative remedial approach that relies on natural attenuation to remediate contaminants dissolved in groundwater. Mechanisms of natural attenuation of BTEX dissolved in groundwater include advection, dispersion, dilution from recharge, sorption, volatilization, and biodegradation. Of these processes, biodegradation is the only mechanism working to transform contaminants into innocuous byproducts. Intrinsic bioremediation occurs when indigenous microorganisms work to bring about a reduction in the total mass of contamination in the subsurface without the addition of nutrients. Patterns

and rates of intrinsic remediation can vary markedly from site to site depending on governing physical and chemical processes.

Three lines of evidence can be used to document and quantify the occurrence of intrinsic remediation (National Research Council, 1993; Wiedemeier et *al.*, 1995): 1) documented loss of contaminant mass at the field scale; 2) geochemical evidence; and 3) microbial evidence. All three lines of evidence are used herein to demonstrate the occurrence of intrinsic remediation at Site ST-29, as described in Section 4.

1.1 SCOPE AND OBJECTIVES

Parsons ES, in conjunction with researchers from the United States Environmental Protection Agency (USEPA) Robert S. Kerr Environmental Research Laboratory (RSKERL), was retained by the AFCEE to conduct site characterization and groundwater modeling in support of intrinsic remediation (natural attenuation) with long-term monitoring as part of a nation-wide, multi-site demonstration program.

The intent of the intrinsic remediation demonstration program sponsored by AFCEE is to develop a systematic process for scientifically investigating and documenting naturally occurring subsurface attenuation processes that can be factored into overall site remediation plans. The objective of the program and this specific demonstration is to provide solid evidence of intrinsic remediation of dissolved fuel hydrocarbons in groundwater so that this information can be used by the Base and its prime environmental contractor(s) to develop an effective groundwater remediation strategy. As a result, these demonstrations are not necessarily intended to fulfill specific federal or state requirements regarding site assessments, remedial action plans (RAPs), or other such mandated investigations and reports. A secondary goal of this multi-site initiative is to provide a database from multiple sites that demonstrates that natural processes of contaminant degradation often can reduce contaminant concentrations in groundwater to below acceptable cleanup standards before potential receptor exposure pathways are completed.

The scope of work for this project involved the following tasks:

- Reviewing existing hydrogeologic and soil and groundwater quality data for the site;
- Conducting supplemental site characterization activities to determine the nature and extent of soil and groundwater contamination and to collect geochemical data in support of intrinsic remediation;

- Developing a conceptual hydrogeologic model of the shallow saturated zone, including the current distribution of contaminants and probable contaminant pathways;
- Determining if natural processes of contaminant destruction are occurring in groundwater at the site;
- Performing contaminant fate and transport modeling based on site hydrogeologic conditions using the Bioplume II model;
- Evaluating a range of model input parameters to determine the sensitivity of the model to those parameters and to consider several contaminant fate and transport scenarios;
- Determining if naturally occurring processes are sufficient to minimize BTEX plume expansion so that groundwater quality standards can be met at a downgradient point of compliance (POC);
- Conducting a preliminary exposure assessment for fuel hydrocarbon contamination in groundwater;
- Developing remedial action objectives (RAOs) and reviewing available remedial technologies;
- Using the results of modeling to recommend the most appropriate remedial option based on specific effectiveness, implementability, and cost criteria; and
- Providing an LTM plan that includes LTM and POC well locations and a sampling and analysis plan (SAP).

Site characterization activities in support of intrinsic remediation included grab sampling of groundwater at cone penetrometer testing (CPT) locations, soil sample collection and analysis, groundwater monitoring point installation using the cone penetrometer, and sampling and analysis of groundwater from newly installed and existing monitoring wells and points.

Site-specific data were used to develop a fate and transport model for the site using Bioplume II and to conduct a preliminary exposure pathways analysis. The Bioplume II model was used to simulate the movement and degradation of BTEX in the shallow saturated zone under the influence of advection, dispersion, sorption, and biodegradation. As part of the TS, this modeling effort had three primary objectives: 1) to predict the future extent and concentration of a dissolved contaminant plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation; 2) to assess the possible risk to potential downgradient receptors by

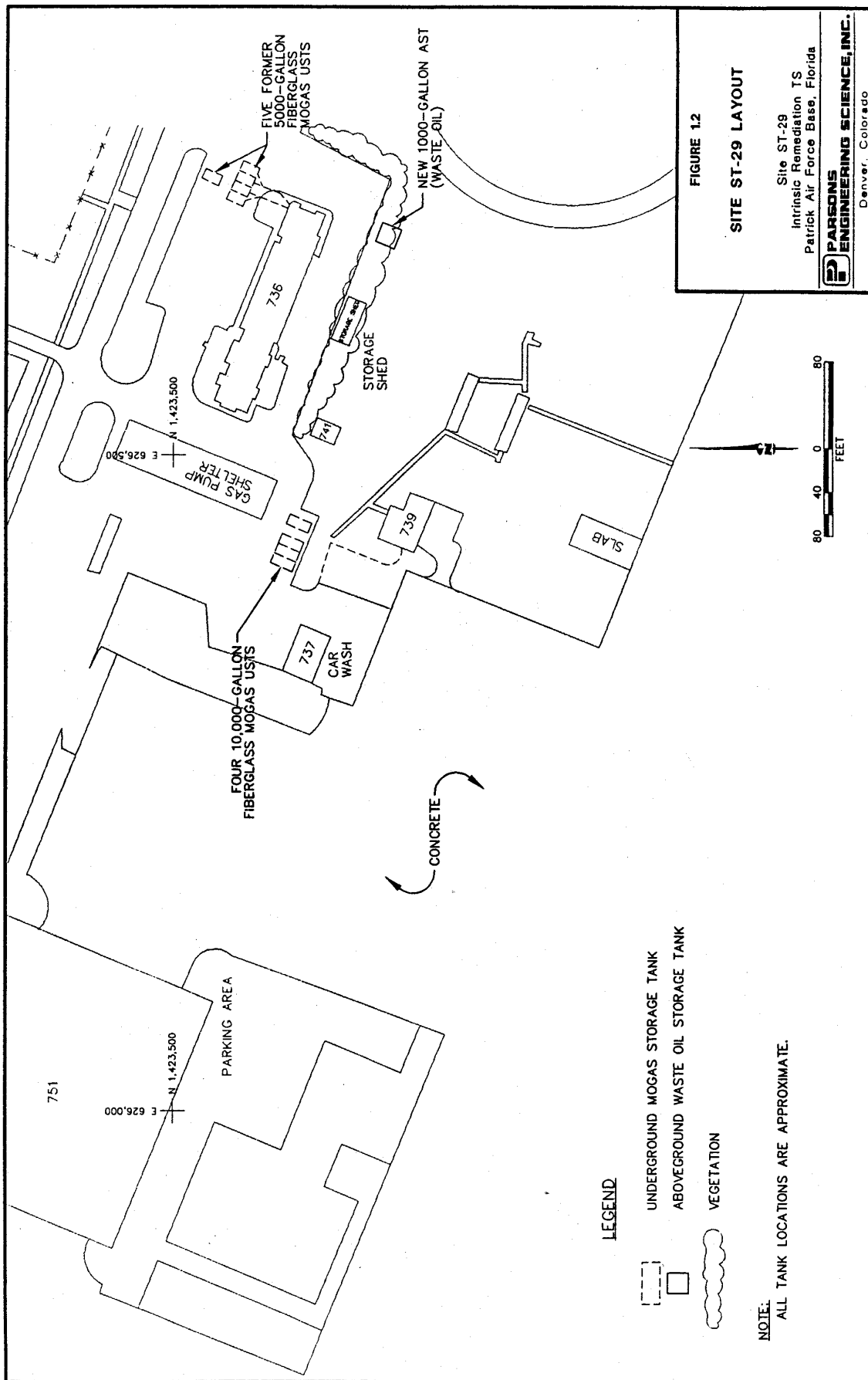
conducting a preliminary exposure pathways analysis; and 3) to provide technical support for the intrinsic remediation with LTM remedial option at regulatory negotiations, as appropriate.

Bioventing and natural contaminant attenuation with LTM were evaluated during this TS. All hydrogeologic and groundwater chemical data necessary to evaluate these remedial options were collected under this program; however, the field work conducted under this program was oriented toward the collection of hydrogeologic data to be used as input into the Bioplume II groundwater model in support of intrinsic remediation with LTM for restoration of fuel-hydrocarbon-contaminated groundwater.

This report contains nine sections, including this introduction, and four appendices. Section 2 summarizes site characterization activities. Section 3 summarizes the physical characteristics of the study area. Section 4 describes the nature and extent of soil and groundwater contamination and the geochemistry of soil and groundwater at the site. Section 5 describes the Bioplume II model and design of the conceptual model for the site, lists model assumptions and input parameters, and describes sensitivity analyses, model output, and the results of the Bioplume II modeling. Section 6 presents a comparative analysis of remedial alternatives. Section 7 presents the LTM plan for the site. Section 8 presents the conclusions of this work and provides recommendations for further work at the site. Section 9 lists the references used to develop this document. Appendix A contains CPT logs, monitoring point completion diagrams, and slug test results. Appendix B presents soil and groundwater analytical results. Appendix C contains model input and calculations related to model calibration, and Appendix D contains Bioplume II model results in ASCII format on a diskette.

1.2 FACILITY BACKGROUND

Patrick AFB lies on a narrow barrier island off the eastern coast of Florida in Brevard County (Figure 1.1). Site ST-29 (Figure 1.2) is located in the north-central section of Patrick AFB and is approximately 400 feet west of the northeastern end of the northeast/southwest (NE/SW) runway. The BX Service Station has been in operation since 1954. The site consists of a small food market (Building 736), a gasoline dispensing area, and a car wash facility (Building 737). Four 10,000-gallon fiberglass MOGAS underground storage tanks (USTs) and one 1,000-gallon waste oil aboveground storage tank (AST) are currently used to dispense or store petroleum products.



1.2.1 Operational and Site Investigation History

In 1973, five 5,000-gallon MOGAS USTs previously located northeast of Building 736 (the BX Service Station) were removed (Figure 1.2), and the excavations were backfilled with sand. In the same year, the MOGAS tanks were replaced with five 10,000-gallon fiberglass USTs. In 1985, one of the 10,000-gallon MOGAS USTs and product lines another of the 10,000-gallon fiberglass USTs were discovered to be leaking. Between 1985 and 1986, an estimated 700 gallons of unleaded gasoline was released into the subsurface as a result of the leaking lines and tank. In 1986, the leaking 10,000-gallon MOGAS UST was removed, leaving the four MOGAS USTs currently in operation. Records describing remedial activities conducted to mitigate the leaking tank and line were not available for review during preparation of this report. In February 1992, a 500-gallon waste oil UST was removed and replaced with the 1,000-gallon waste oil AST currently in use.

The Air Force Installation Restoration Program (IRP) was initiated at Patrick AFB in 1984 when the Air Force Engineering and Services Center (AFESC) retained Environmental Science & Engineering, Inc. (ESE) to conduct a records search of previous Base activities (Phase I of the IRP) (ESE, 1984). Phase II (stage 1) IRP work at Patrick AFB began in 1985 and consisted of monitoring well installation and collection and analysis of groundwater, soil, sediment, and surface water samples at a total of 16 sites (ESE, 1988). The BX Service Station (ST-29) was identified and added to the IRP during Phase II (stage 2) activities (ESE, 1988). Phase II (stage 2) work involved two sampling events to determine fluctuations in groundwater levels at the site. Round 1 sampling was conducted from late November 1988 to January 1989. Round 2 sampling was conducted from October to November 1989. A technical report documenting the results of stage 2 work was finalized in December of 1990 (ESE, 1991). A Phase II (stage 3) program at the BX Service Station was performed by O'Brien & Gere Engineers, Inc. (1992) in accordance with the Florida Department of Environmental Regulations (FDER) Petroleum Contamination Assessment (PCA) guidelines, as outlined in Chapters 17-770.600 and 17-770.630 of the Florida Administrative Code (FAC). The objective of the Phase II (stage 3) investigation was to evaluate the nature and extent of contamination at the site and to make remedial recommendations. A finalized report of the Phase II (stage 3) study was not available at the time this work plan was written.

A soil gas survey was conducted by ES (1993) at the BX Service Station in January 1993, prior to installation of a bioventing pilot test system. A 20-foot by 20-foot grid was laid out in the field area where previous sampling had determined that soil hydrocarbon contamination was present. Total volatile petroleum hydrocarbons (TVPH) exceeded 10,000 parts per million, volume per volume (ppmv) at locations adjacent to the north and east sides of the car wash (Building 737) at Site ST-29.

1.2.2 Current Remedial Activities

A pilot-scale bioventing system is currently in place to treat the soil contamination north and east of the car wash. Initial results from this pilot test have been promising, with excellent biodegradation rates measured throughout a 3,000-square-foot area north of Building 737. Details regarding this system are presented in a bioventing work plan and interim results report(ES, 1993).

SECTION 2

SITE CHARACTERIZATION ACTIVITIES

This section presents the methods used by Parsons ES and researchers from the RSKERL to collect site-specific data at Patrick AFB, Florida. The majority of the site characterization data obtained under this program were collected in March 1994. In addition to the March 1994 site characterization activities, groundwater samples were collected in monitoring points and monitoring wells in March 1995 by RSKERL researchers and in May 1995 by CH2M Hill. To meet the requirements of the intrinsic remediation demonstration, several investigative techniques, including soil and groundwater sampling and aquifer testing, were utilized. CPT was used to collect stratigraphic information, and to collect soil samples. Previous investigations conducted at the site utilized standard hollow-stem auger (HSA) drilling and soil sampling. Groundwater samples were collected at monitoring points installed in CPT holes, and at previously installed monitoring wells. Previous investigations utilized monitoring wells installed in HSA boreholes. Aquifer slug tests were conducted in existing wells.

Data collected under this program were integrated to develop the conceptual site model and to aid interpretation of the physical setting (Section 3) and contaminant distribution (Section 4). The physical and chemical hydrogeologic data listed below were collected during the field work phase of the TS:

- Depth from measurement datum to the water table or potentiometric surface in monitoring wells and monitoring points;
- Location of potential groundwater recharge and discharge areas;
- Hydraulic conductivity as determined through slug tests;
- Stratigraphic analysis of subsurface media;
- Estimation of extent and thickness (if present) of mobile LNAPL;
- Dissolved oxygen (DO), nitrate, ferrous iron, sulfate, chloride, and total organic carbon (TOC) concentrations in groundwater;

- Temperature, specific conductance, reduction oxidation (redox) potential, total alkalinity, and pH of groundwater;
- BTEX and trimethylbenzene (TMB) concentrations in groundwater; and
- BTEX and TMB concentrations in soil.

The following sections describe the procedures that were followed when collecting site specific data. The applied CPT, soil sampling, and groundwater monitoring point installation and development procedures are described in Section 2.1. Procedures for sampling existing monitoring wells and newly installed monitoring points are described in Section 2.2. Aquifer testing procedures are described in Section 2.3.

2.1 CONE PENETROMETRY, MONITORING POINT INSTALLATION, AND SOIL SAMPLING ACTIVITIES

CPT-related activities took place between March 22 and March 31, 1994. CPT, soil sampling, and groundwater monitoring point installation were accomplished using the procedures described in the following sections and in the site-specific work plan. Subsurface conditions at Site ST-29 were characterized using CPT coupled with laser induced fluorescence (LIF). Cone penetrometry is an expeditious and effective means of analyzing the stratigraphy at a site by measuring the resistance of different soil types against the conical probe of the penetrometer as it is pushed into the subsurface. The resistance on the pressure tip and friction sleeves on the side of the cone is then correlated to soil cores collected to calibrate the CPT readings to the lithologies present at the site. Methodologies for the collection of soil core data are described in Section 2.1.3. The purpose of the LIF/CPT sampling at Site ST-29 was to determine subsurface stratigraphy and to help delineate the extent of mobile LNAPL (if present) and dissolved BTEX plumes.

CPT was conducted using the Applied Research Associates, Inc. (ARA) cone penetrometer truck, which consists of an instrumented probe that is forced into the ground using a hydraulic load frame mounted on a truck with the weight of the truck providing the necessary reaction mass. The penetrometer equipment is mounted inside an 18-foot van body attached to a 10-wheel truck chassis with a turbo-charged diesel engine. Ballast in the form of metal weights and a steel water tank, which can hold 5,000 pounds of water, is added to the

truck to achieve an overall push capability of 45,000 pounds. Penetration force is supplied by a pair of large hydraulic cylinders bolted to the truck frame.

The penetrometer probe is of standard dimensions, having a 1.405-inch outside diameter (OD), 60-degree conical tip, and a 1.405-inch OD by 5.27-inch-long friction sleeve. A pressure gauge located above the cone tip monitors the pore water pressure so that corrected estimates of water depth and permeability can be made. Inside the probe, two load cells independently measure the vertical resistance against the conical tip and the side friction along the sleeve. Each load cell inside the probe is a cylinder of uniform cross section that is instrumented with four strain gauges in a full-bridge circuit. Forces are sensed by the load cells, and the data are transmitted from the probe assembly via a cable running through the push tubes. The analog data are digitized, recorded, and plotted by computer in the penetrometry truck. The penetrometer is usually advanced vertically into the soil at a constant rate of 48 inches per minute, although this rate must sometimes be reduced (e.g., when hard layers are encountered). The magnitude of the penetration pore pressure is a function of compressibility and, most importantly, permeability. Penetration, dissipation, and resistivity data will be used to determine soil types as they are encountered in the field.

The known propensity of aromatic or chlorinated hydrocarbons to fluoresce under ultraviolet wavelengths has allowed the use of LIF technology in conjunction with CPT technology to detect soil characteristics and hydrocarbon contamination simultaneously. The LI:E;/CPT system has a sapphire window in the side of the CPT pressure cone that allows a laser to scan the soil for fluorescent compounds as the LIF/CPT rod is pushed through soil. Assuming that aromatic hydrocarbons are simultaneously solvenated with other fuel-hydrocarbon constituents, the magnitude of aromatic fluorescence is indicative of hydrocarbon contamination in a soil matrix. A fiber optic cable connected to the laser spectrometer, and a 6-pair electrical conductor connected to the CPT data acquisition system, are routed through the interior of the push tubes to the CPT probe.

The basic laser system components of the CPT/LIF instrumentation are a Nd:YAG[®] pump laser, two separate and independent dye lasers, frequency-doubling crystals that convert the visible-dye laser output to ultraviolet, a fiber optic probe, a monochromator for wavelength resolution of the return fluorescence, a photomultiplier tube to convert photons into an electrical signal, a digital oscilloscope for waveform capture, and a control computer. The fiber optic probe for the cone penetrometer consists of a delivery and collection fiber, a protective sheath, a fiber

optic mount within the cone, and a sapphire window (Figure 2.1) The uphole portion of the system is adaptable to either groundwater monitoring fiber optic probes or an optical cone penetrometer probe. Optimal wavelengths to be used during a continuous CPT push are determined from initial data. Wavelength is selected to give the strongest fluorescence signal that can be attributed to the presence of contamination. Past experience suggested that a wavelength of less than 275 nanometers (nm) may be appropriate for detecting the fluorescence of BTEX.

2.1.1 CPT and Groundwater Monitoring Point Locations

CPT and/or groundwater monitoring point installation was performed at 25 locations in the vicinity of Site ST-29. All CPT and/or monitoring point locations are indicated on Figure 2.2, except for location CPT-25. CPT-25 was installed approximately 400 feet south-southwest of the BX Service Station (Building 736). At 23 of the 25 sites, groundwater monitoring points were installed. At the remaining two CPT sites, only soil characteristics and LIF data were recorded. Multiple groundwater monitoring points (with screens at different depths) were installed at several of the CPT locations. At eight of the locations where monitoring points were installed, the CPT unit was used only to install the points; no soil data were collected due to a failure in the probe instrumentation. Soil samples for laboratory analysis were collected at eight of the sites. Table 2.1 summarizes the CPT-related activity undertaken at each location. CPT locations were selected to provide the hydrogeologic data necessary for successful implementation of the Bioplume II model.

2.1.2 Groundwater Monitoring Point Installation Procedures

This section describes the procedures and equipment used for installation of new groundwater monitoring points with the CPT apparatus.

2.1.2.1 Pre-Installation Activities

All necessary digging, drilling, and groundwater monitoring well installation permits were obtained prior to mobilizing to the field. In addition, all utility lines were located, and proposed drilling locations were cleared prior to any drilling activities.

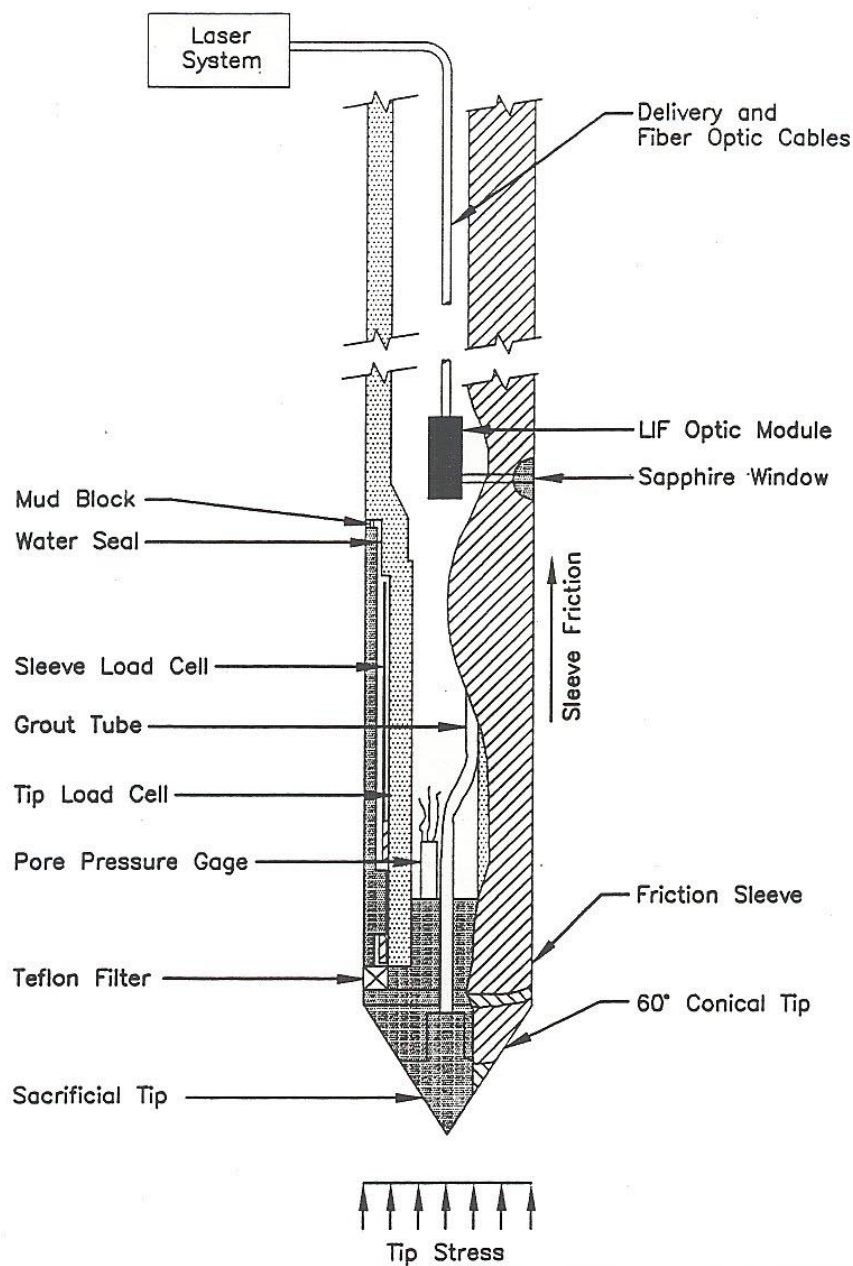


FIGURE 2.1

**SCHEMATIC OF LASER-INDUCED
FLUORESCENCE CONE
PENETROMETER PROBE**

Site ST-29
Intrinsic Remediation TS
Patrick Air Force Base, Florida

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

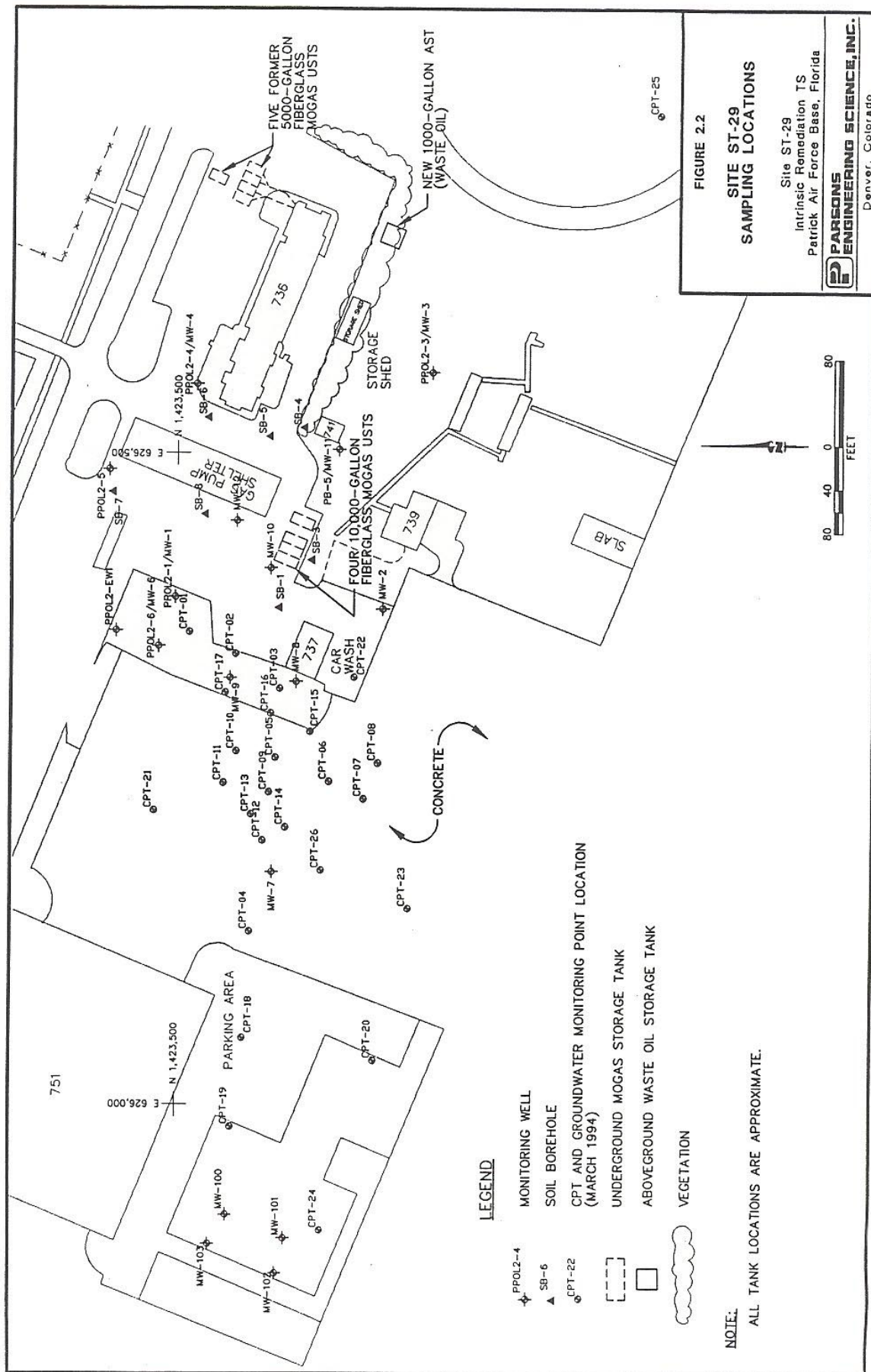


TABLE 2.1
CPT ACTIVITY SUMMARY
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Location	Northing	Easting	Ground Elevation (ft msl) ^{a/}	Total Depth (ft bgs) ^{b/}	Depth to Top of Screen (ft bgs)	Depth to Base of Screen (ft bgs)	CPT Profile Available?	Soil Sample Intervals (ft bgs)
CPT-01	626491	1423363	7.02	8.28	5	8.28	Y	NS ^{c/}
CPT-02S	626455	1423346	7.07	8.04	4.37	7.65	Y	4 - 5
CPT-86-002D	626455	1423346	7.07	13.42	10.14	13.42	Y	5 - 6 6 - 6.45 6.45 - 6.67 6.67 - 7 7 - 8
CPT-03S	626420	1423319	6.55	8.19	4.592	7.872	Y	3 - 4.5
CPT-03M	626420	1423319	6.55	14.1	10.82	14.1	Y	4.5 - 5.5
CPT-03D	626420	1423319	6.55	19.45	15.762	19.042	Y	5.5 - 6.5 6.5 - 7
CPT-04S	626443	1423133	6.57	10	6.64	9.92	Y	NS
CPT-04D	626443	1423133	6.57	11.92	8.26	11.54	Y	NS
CPT-05S	626423	1423266	6.26	8	4.72	8	Y	3.33 - 3.92 4.17 - 4.75 5.00 - 5.58 5.33 - 5.83
CPT-06S	626381	1423248	6.26	8	4.72	8	Y	NS
CPT-07S	626354	1423235	6.36	1.44	5.12	1.44	Y	NS
CPT-08S	626343	1423262	6.48	8	4.72	8	Y	NS
CPT-09S	626428	1423240	6.35	7.98	4.72	8	Y	2.5 - 3.5
CPT-09D	626428	1423240	6.35	15	11.72	15	Y	3.5 - 4.5 4.5 - 5.5 5.5 - 6.5
CPT-10S	626454	1423271	6.26	8	4.72	8	Y	NS
CPT-11S	626464	1423247	6.37	8	4.72	8	Y	NS
CPT-12S	626433	1423203	6.43	8.09	4.72	8	Y	NS
CPT-12D	626433	1423203	6.43	16	12.72	16	Y	NS
CPT-13S	626442	1423223	6.41	17.49	14.21	17.49	Y	4.5 - 6.5
CPT-14D	626415	1423213	6.36	16.73	13.45	16.73	Y	NS
CPT-15				19.39				3 - 4 4 - 5 5 - 6 5.5 - 6.5

TABLE 2.1 (CONCLUDED)
CPT ACTIVITY SUMMARY
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Location	Northing	Easting	Ground Elevation (ft msl) ^{a/}	Total Depth (ft bgs) ^{b/}	Depth to Top of Screen (ft bgs)	Depth to Base of Screen (ft bgs)	CPT Profile Available?	Soil Sample Intervals (ft bgs)
CPT-16S	626427	1423300	6.14	8	4.72	8	Y	3 - 5.35
CPT-16DD	626427	1423300	6.14	45	41.72	45	Y	5.35 - 6.53 6.53 - 7.7
CPT-17				14.60			Y	2 - 3 3 - 4 4 - 5 5 - 6
CPT-18S	626448	1423051	6.58	7.87	4.72	8	N	NS
CPT-18D	626448	1423051	6.58	16	12.72	16	N	NS
CPT-18DD	626448	1423051	6.58	40	36.72	40	N	NS
CPT-19S	626457	1422983	6.39	8	4.72	8	N	NS
CPT-19D	626457	1422983	6.39	16	12.72	16	N	NS
CPT-20S	626345	1423034	6.4	8	4.72	8	N	NS
CPT-20D	626345	1423034	6.4	16	12.72	16	N	NS
CPT-21S	626518	1423226	6.49	7.9	4.72	8	N	NS
CPT-21D	626518	1423226	6.49	15.3	12.02	15.3	N	NS
CPT-22S	626362	1423328	6.75	7.9	4.77	8.05	Y	NS
CPT-22D	626362	1423328	6.75	10.2	10.17	13.45	Y	NS
CPT-23S	626319	1423151	6.57	6.94	3.72	7	N	NS
CPT-23D	626319	1423151	6.57	13.43	10.22	13.5	N	NS
CPT-24S	626386	1422903	5.89	6.46	3.22	6.5	N	NS
CPT-24D	626386	1422903	5.89	12.94	9.72	13	N	NS
CPT-25S	626129	1423761	6.6	6.47	3.22	6.5	N	NS
CPT-25D	626129	1423761	6.6	12.83	9.72	13	N	NS
CPT-26S	626387	1423180	6.47	6.87	3.72	7	N	NS
CPT-26D	626387	1423180	6.47	13.41	10.22	13.5	N	NS

^{a/} ft msl = feet above mean sea level.

^{b/} ft bgs = feet below ground surface.

^{c/} NS = no soil sample collected

Water used in equipment cleaning or grouting was obtained from an onsite potable water supply. Water use approval was verified by contacting the appropriate facility personnel.

2.1.2.2 Equipment Decontamination Procedures

After sampling at each CPT location, CPT push rods were cleaned with ARA's CPT steam-cleaning system (rod cleaner) as the rods were withdrawn from the ground. A vacuum system located beneath the CPT truck was used to recover cleaning water. Use of this system resulted in nearly 100-percent recovery of steam-cleaning rinseate from the rod cleaner. Rinseate was generated only as the rods moved past the cleaner, thereby minimizing liquid waste generation. Rinseate was collected in 55-gallon drums provided by ARA. Filled 55-gallon drums were then emptied into a 6,000-gallon hazardous waste collection tank used as a Base-wide disposal tank for Patrick AFB operations.

Potable water to be used in CPT equipment cleaning, decontamination, or grouting was obtained from one of the Base water supplies. Water use approval was verified by contacting the appropriate facility personnel. Precautions were taken to minimize any impact to the surrounding area that might result from decontamination operations.

Fuel, lubricants, and other similar substances were handled in a manner consistent with accepted safety procedures and standard operating practices. Well completion materials were not stored near or in areas which could be affected by these substances.

2.1.2.3 Monitoring Point Installation

Groundwater monitoring points were installed at several locations under this program. Detailed well installation procedures are described in the following paragraphs. At most locations, two or three separate points (each screened at different depths) were installed. At each location, the point with the shallowest screened interval was designated with the suffix "S", while the deep point was designated with the suffix "D" (e.g., CPT-02S or CPT-02D). At CPT-03, CPT-16, and CPT-18, three points were installed. At CPT-03, the intermediate point was called CPT-03M, while at CPT-16 and CPT-18, the intermediate points were given the "D" suffix and the deepest points were given the suffix "DD". Well completion diagrams are included in Appendix A.

2.1. 2. 3.1 Monitoring Point Materials Decontamination

Well completion materials were inspected by the field hydrogeologist and determined to be clean and acceptable prior to use. All well completion materials were factory sealed. Materials were inspected for possible external contamination before use. Materials that could not be cleaned to the satisfaction of the field hydrogeologist were not used.

2.1. 2. 3.2 Monitoring Point Screen and Casing

Upon completion of CPT to the proper termination depth, monitoring point casing was installed. Construction details were noted on a Monitoring Point Installation Record form. This information became part of the permanent field record for the site.

Blank well casing was constructed of either Schedule 40 polyvinyl chloride (PVC) with an inside diameter (ID) of 0.5 inch or Teflon[®] tubing with an ID of 0.25 inch. All well casing sections were flush-threaded; glued joints were not used. The casing or tubing at each well was fitted with a top cap constructed of the same type of material as the casing/tubing. The top cap was vented to maintain ambient atmospheric pressure within the well casing. The purpose of using the Teflon[®] tubing was to field test the ability to connect this tubing directly to the PVC screen and successfully obtain a groundwater sample via the tubing.

Well screens were constructed of flush-threaded, Schedule 40 PVC with an ID of 0.5 inch. The screens were factory slotted with 0.010-inch openings. Where blank casing was also 0.5inch ID, the screen was threaded to the casing. For the points where a Teflon[®] tube was used, a brass pipe fitting was used to connect the screen and the tube. Each well had a 1-meter screen. The position of the screen was selected by the field hydrogeologist after consideration was given to the geometry and hydraulic characteristics of the stratum in which the wells were screened.

The field hydrogeologist verified and recorded the hole depth and the lengths of all casing sections. All lengths and depths were measured to the nearest 0.1 foot.

2.1.2.3.3 Flush-Mount protective Cover

Each monitoring point was completed with an at-grade protective cover. In areas with pavement, the at-grade covers were cemented in place using concrete blended to the existing pavement. All

wells were completed with concrete pads that slope gently away from the protective casing to facilitate runoff during precipitation events.

2.1.2.4 Monitoring Point Development

Before being sampled, newly installed monitoring points were developed. Well development removes sediment from inside the well casing and flushes fines, cuttings, and drilling fluids from the sand pack and the portion of the formation adjacent to the well screen.

Monitoring point development was accomplished using a peristaltic pump. In points with PVC casing, the pump tubing was regularly lowered to the bottom of the well so that fines were agitated and removed from the well in the development water. For points with Teflon[®] tubing as the well casing, the pump was attached to the tubing and used to remove water. Development was continued until a minimum of 10 casing volumes of water were removed from the well and the pH, temperature, specific conductivity, DO concentration, and redox potential of the groundwater had stabilized. All well development waters were collected in 55-gallon drums and transported to the Patrick AFB waste collection tank.

2.1.2.5 Water Level Measurements

Water levels were measured at monitoring points with PVC casing. Measurements were made using an electric water level probe capable of recording to the nearest 1/8 inch (0.01 foot). Water levels could not be measured in points constructed with Teflon[®] casing because the casing was too small to accommodate the water level probe. Additional water level measurements were also made in several existing monitoring wells, although these measurements were not collected on the same day as measurements made at monitoring points.

2.1.2.6 Well Location and Datum Survey

The location and elevation of the new wells were surveyed by ARA personnel soon after well completion. The horizontal locations were measured relative to established Patrick AFB coordinates. Horizontal coordinates were measured to the nearest 1 foot. Vertical location of the adjacent ground surface was measured relative to a US Geological Survey (USGS) mean sea level (msl) datum. The ground surface elevation was measured to the nearest 0.01 foot, and the

distance from the ground surface to the measurement datum was later measured to the nearest 0.01 foot by hand. Survey results are presented in Table 2.1.

2.1.3 Soil Sampling

Soil samples were obtained from eight CPT holes (Table 2.1) using a Mostap-35[®] sampling device. The sampler is coupled to the penetrometer rod and pushed into the soil with the same equipment used for CPT/LIF. While the Mostap-35[®] cone is in position, soil is prevented from entering the sampling tube until the desired depth is achieved. After the sampler was pushed to the depth at which the soil sample was to be taken, the sampling unit was raised a few inches, and the Mostap-35[®] apparatus was unlocked. After unlocking the Mostap-35[®] attachment, a soil section was cut, and the sampling apparatus was pulled from the ground as quickly as possible. The Mostap-35X sampling apparatus allowed collection of 2-foot-long continuous samples. Recovery efficiencies for samples in saturated soils were occasionally reduced because of spillage of the soil from the device after extraction. To mitigate this problem, soil samples were compressed *in situ* with the penetrometer and Mostap assembly to expel the pore water before extraction. Compressed soil samples were then extracted and measured to give a description of the soil stratigraphy accurate for the length of soil core taken.

Soil samples collected for laboratory analysis were removed from the sampler and placed in clean glass jars. In addition to samples collected with the CPT, shallow soil stratigraphy was examined at two locations (CPT-3 and CPT-5) by digging test holes with a post-hole digger. Soil sample locations and depths are summarized on Table 2.1.

Parsons ES field personnel observed CPT and monitoring point installation activities and maintained a log documenting any unusual conditions encountered during installation. ARA kept logs of CPT instrument readings and presented the results as strip charts in their report on site activities (Gildea *et al.*, 1994). Final CPT logs are presented in Appendix A. These logs indicate lithologic characteristics and contacts as indicated by CPT readings, as well as sample intervals and laboratory results for total BTEX analyses.

All soil sampling tools were cleaned onsite prior to use and between each sampling event with a clean water/phosphate-free detergent mix and a clean water rinse. All decontamination activities were conducted in a manner so that the excess water was contained and properly disposed of.

2.2 GROUNDWATER SAMPLING

This section describes the procedures used for collecting groundwater quality samples in March 1994. Groundwater sampling conducted at this time followed established USEPA procedures, as did the groundwater sampling that occurred in March 1995. The sampling protocol followed by CH2M Hill during the May 1995 sampling event was not available at the time of this report. In order to maintain a high degree of quality control during this sampling event, the procedures described in the following sections were followed during the March 1994 sampling event.

Groundwater samples were collected during and after installation of monitoring points. Existing wells were sampled by Parsons ES and/or RSKERL personnel while new monitoring points were being installed. Sampling of monitoring wells and points is described in Section 2.2.3.1. Sample analysis was performed by USEPA RSKERL personnel.

Activities that occurred during groundwater sampling are summarized below:

- Assembly and preparation of equipment and supplies;
- Inspection of the well integrity (for monitoring well sampling), including
 - Protective cover, cap, and lock
 - External surface seal and pad,
 - Well stick-up, cap, and datum reference, and
 - Internal surface seal;
- Groundwater sampling, including
 - Water level measurements,
 - Visual inspection of water,
 - Well casing or monitoring point evacuation, and
 - Sampling;
- Sample preservation and transport, including
 - Sample preparation,
 - Onsite measurement of physical parameters,
 - Sample labeling,

- Transport of samples to the onsite USEPA mobile laboratory;
- Completion of sampling records; and
- Sample disposition.

Detailed groundwater sampling and sample handling procedures that were used are presented in following sections.

2.2.1 Groundwater Sampling Locations

Groundwater samples were collected from existing monitoring wells and from newly installed groundwater monitoring points.

2.2.1.1 Monitoring Well Sampling Locations

Groundwater samples were collected from seven existing monitoring wells. Existing wells that were sampled include MW-100 through MW-103 (installed as part of the monitoring system for a UST site present to the west of Site ST-29), PB-5, PPOL2-1, and PPOL2-6. These wells were sampled using a peristaltic pump with dedicated polyethylene tubing. Locations of these wells are indicated on Figure 2.2.

2.2.1.2 Monitoring Point Locations

Groundwater samples were collected from 41 monitoring points at 23 locations. After completion of installation and development activities, monitoring points were sampled using a peristaltic pump and dedicated tubing (where needed). Locations of groundwater monitoring points are indicated on Figure 2.2.

2.2.2 Preparation for Sampling

All equipment used for sampling was assembled and properly cleaned and calibrated (if required) prior to arriving in the field. In addition, all record-keeping materials were gathered prior to leaving the office.

2.2.2.1 Equipment Cleaning

All portions of sampling and test equipment that contacted the samples were thoroughly cleaned before use. This equipment included the water level probe and cable, lifting line, test equipment for onsite use, and other equipment that contacted the samples or was placed downhole. The following cleaning protocol was used:

- Cleaned with potable water and phosphate-free laboratory detergent;
- Rinsed with potable water;
- Rinsed with distilled or deionized water;
- Rinsed with reagent-grade acetone; and
- Air dried prior to use.

Any deviations from these procedures were documented in the field scientist's field notebook and on the groundwater sampling form.

2.2.2.2 Equipment Calibration

As required, field analytical equipment was calibrated according to the manufacturer's specifications prior to field use. This applied to equipment used for onsite chemical measurements of DO, redox potential, pH, specific conductivity, and temperature.

2.2.3 Sampling Procedures

Special care was taken to prevent contamination of the groundwater and extracted samples through cross contamination from improperly cleaned equipment. Water level probes and cable used to determine static water levels and well total depths were thoroughly cleaned before and after field use and between uses at different sampling locations according to the procedures presented in Section 2.2.2.1. In addition, a clean pair of new, disposable nitrile gloves was worn each time a different well was sampled.

2.2.3.1 Groundwater Monitoring Well and Monitoring Point Sampling

2.2.3.1.1 *Preparation of Location*

Prior to starting the sampling procedure, the area around the existing wells and new monitoring points was cleared of foreign materials, such as brush, rocks, and debris. This prevented sampling equipment from inadvertently contacting debris around the monitoring well/point.

2.2.3.1.2 *Water Level and Total Depth Measurements*

Prior to removing any water from the monitoring well or monitoring point, the static water level was measured. An electric water level probe was used to measure the depth to groundwater to the nearest 0.01 foot below the datum. After measuring the static water level, the water level probe was slowly lowered to the bottom of the monitoring well/point, and the total depth was measured to the nearest 0.01 foot. Based on these measurements, the volume of water to be purged from each monitoring well/point was calculated.

2.2.3.1.3 *Monitoring Well/Point Purging*

The volume of water contained within the monitoring well/point casing at the time of sampling was calculated, and at least three times the calculated volume was removed from the well/point. USEPA RSKERL and Parsons ES persoMe1 monitored temperature and DO concentrations during purging, and purging continued until these parameters stabilized, and at least three casing volumes were removed. All purge water was placed in ARA-provided, 55gallon drums and disposed of by ARA in the Patrick AFB 6,000-gallon hazardous waste collection tank. Emptied drums were rinsed with hot water and returned to Base personnel for reuse. A peristaltic pump was used for monitoring well and monitoring point purging.

2.2.3.1.4 *Sample Extraction*

Dedicated high-density polyethylene (HDPE) tubing and a peristaltic pump were used to extract groundwater samples from the monitoring wells and points. For points with Teflon[®] tubing/casings, the pump was attached directly to the casing. Where possible, the tubing was lowered through the casing into the water gently to prevent splashing. The sample was

transferred directly into the appropriate sample container(s), with water carefully poured down the inner walls of the sample bottle to minimize aeration of the sample.

Excess water collected during sampling was placed into the 55-gallon drums used for monitoring well/point purge waters and transported by ARA to the 6,000-gallon hazardous waste collection tank at Patrick AFB.

2.2.4 Onsite Chemical Parameter Measurement

2.2.4.1 Dissolved Oxygen Measurements

DO measurements were taken using an Orion[®] model 840 DO meter. DO concentrations were determined by extracting groundwater from the subsurface using a peristaltic pump, and running the extracted groundwater over the probe of the DO meter while the probe was immersed in an Erlenmeyer flask. This effectively produces a flow-through cell that minimizes aeration of the sample. DO concentrations were recorded after the readings stabilized and in all cases represent the lowest DO concentration observed.

2.2.4.2 Reduction/Oxidation Potential Measurements

Redox potential measurements were taken using an Orion[®] model 290A redox potential meter. Redox potential measurements were recorded after the readings stabilized and generally represent the lowest redox potential observed.

2.2.4.3 pH, Temperature, and Electric Conductance

Because the pH, temperature, and electric conductance of the groundwater change significantly within a short time following sample acquisition, these parameters were measured in the field or in the USEPA Mobile Laboratory immediately after sample collection. The measurements were made in a clean glass container separate from those intended for laboratory analysis, and the measured values were recorded on the groundwater sampling record.

2.2.5 Sample Handling

2.2.5.1 Sample Preservation

The USEPA Mobile Laboratory added any necessary chemical preservatives to sample containers prior to sampling.

2.2.5.2 Sample Container and Labels

Sample containers and appropriate container lids were provided by the USEPA Mobile Laboratory. The sample containers were filled as described in Section 2.2.3.1.4, and the container lids were tightly closed. The sample label was firmly attached to the container side, and the following information was legibly and indelibly written on the label:

- Facility name;
- Sample identification;
- Sample type (e.g., groundwater);
- Sampling date;
- Sampling time;
- Preservatives added; and,
- Sample collector's initials.

2.2.5.3 Sample Shipment

After the samples were sealed and labeled, they were packaged for transport to the onsite USEPA Mobile Laboratory. The following packaging and labeling procedures were followed:

- Sample was packaged to prevent leakage or vaporization from its container;
- Shipping container was labeled with
 - Sample collector's name, address, and telephone number;
 - Laboratory's name, address, and telephone number; - Description of sample;
 - Quantity of sample; and
 - Date of shipment.

The packaged samples were hand-delivered directly to the USEPA Mobile Laboratory. Delivery occurred shortly after sample acquisition.

2.3 AQUIFER TESTING

2.3.1 Slug Testing

Slug tests were conducted to estimate the hydraulic conductivity of the shallow saturated zone at Site ST-29. Slug tests are single-well hydraulic tests used to determine the hydraulic conductivity of an aquifer in the immediate vicinity of the tested well. Slug tests can be used for both confined and unconfined aquifers that have a transmissivity of less than 7,000 square feet per day (ft²/day). Slug testing can be performed using either a rising head or a falling head test. Rising head tests, which generally give more accurate results, were used at this site. Slug tests were performed in monitoring wells PPOL2-1, PPOL2~, PPOL2-5, and PPOL2-6 (Figure 2.2). Detailed slug testing procedures are presented in the *Draft Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater* (Wiedemeier et al., 1995), hereafter referred to as the Technical Protocol document.

2.3.2 Slug Test Data Analysis

Data obtained during slug testing were analyzed using AQTESOLV software and the methods of Bouwer and Rice (1976) and Bouwer (1989) for unconfined conditions. The results of slug testing are presented in Section 3.3.

SECTION 3

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

This section incorporates data collected during investigations summarized by ESE (1991) and O'Brien and Gere Engineers, Inc. (1992), and a more recent investigation conducted in March 1994, by Parsons ES in conjunction with researchers from the USEPA RSKERL to describe the physical characteristics of Site ST-29. The investigative techniques used by Parsons ES and RSKERL researchers to determine the physical characteristics of Site ST-29 are discussed in Section 2.

3.1 SURFACE FEATURES

3.1.1 Topography and Surface Water Hydrology

Patrick AFB lies on a long barrier island situated off Florida's east coast, in Brevard County. The City of Cocoa Beach is located immediately north of the Base, and Satellite Beach is directly south. Patrick AFB encompasses approximately 1,800 acres of coastal strip that is composed largely of relic beach deposits of the Cocoa-Sebastian Ridge of the Central Atlantic Coastal Strip in the Eastern Flatwoods Physiographic District.

The barrier island parallels the eastern Florida shoreline and is bounded on the east by the Atlantic Ocean and on the west by the Banana River (Figure 1.1). The widest section of the barrier island lies north of Patrick AFB at Cape Canaveral (width 4.5 miles). The island extends approximately 90 miles from Ponce de Leon Inlet south to Sebastian Inlet. Patrick AFB is 4.1 miles long (north to south), and its width varies from 800 feet at its northern end to 7,200 feet at its southern end. The highest elevations of Patrick AFB are located on sand dune features which lie inland from the Atlantic Ocean. These dunes form ridges with elevations of 10 to 20 feet above msl. Elevation of the land surface at the base varies from 0 to 20 feet msl. The land surface at the base slopes gently westward toward the shoreline of the Banana River (Figure 1.1).

The Site ST-29 vicinity has a generally level ground surface that varies from approximately 7 to 8 feet above msl. Portions of this area have been raised or leveled with fill. There are no surface water bodies located in the immediate vicinity of Site ST-29, and the bodies of surface water closest to the site are the Atlantic Ocean (750 feet east) and the Banana River (2,400 feet west) (Figure 1.1).

3.2 REGIONAL GEOLOGY AND HYDROGEOLOGY

Patrick AFB is situated on undifferentiated marine sands overlying the Pleistocene-age Anastasia Formation and Caloosahatchee Marl Formation; these three units comprise the surficial unconsolidated deposits in the area. Above the Caloosahatchee Marl, the surficial deposits form a shallow, unconfined aquifer. The Anastasia Formation is a discontinuous layer of undifferentiated sands with silt and shells that may not be present in this area. The Caloosahatchee Marl Formation consists primarily of calcareous sandy clay deposits.

Underlying the Caloosahatchee Formation is the Tamiami Formation, which is made up of limestones, marls, silty sands, and clay. The Tamiami Formation forms a shallow bedrock aquifer. The marine sands, clays, and limestones of the Hawthorn Formation underlie the Tamiami Formation. Interspersed limestone layers form localized aquifers within the Hawthorn Formation. Beneath the Hawthorn Formation is the Floridan Aquifer, which is comprised of Ocala Formation limestone and extends to a depth of over 1,500 feet below msl. Figure 3.1 shows the generalized stratigraphic sequence for the area.

The likelihood of contamination of the deep aquifers from sources in the shallow aquifer is assumed to be minimal. This is because the deep aquifers have sufficient pressure head to cause the potentiometric surface for the deep aquifers to be greater than that for the water table within the shallow unconfined aquifer, thus preventing vertical groundwater flow (and the associated migration of contaminants) from the shallow aquifer into the deeper units.

Patrick AFB receives its water from the City of Cocoa Beach, which is supplied by inland well fields screened in the Floridan aquifer in East Orange County. A backup water supply for Patrick AFB is supplied by the City of Melbourne. Patrick AFB maintains five standby potable water supply wells, primarily for fire suppression. These wells are screened in the limestones of the Ocala Formation (ESE, 1984). Groundwater in the surficial aquifer beneath Site ST-29 is classified as G-II based on Chapter 3 of the FAC regulations [designated as potable if less than 10,000 milligrams per liter (mg/L) of total dissolved solids (TDS) is present.

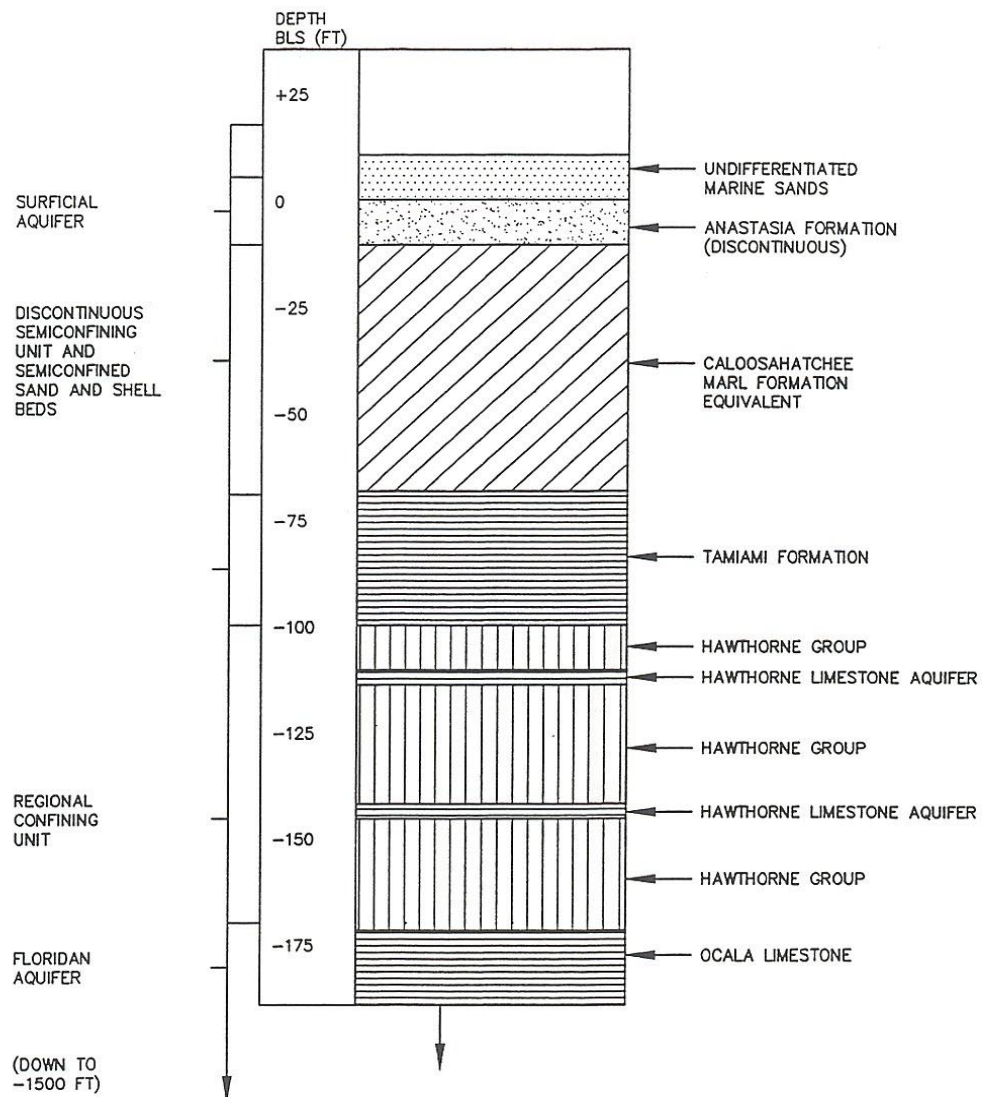


FIGURE 3.1

**GENERALIZED STRATIGRAPHIC
SEQUENCE**

Site ST-29
Intrinsic Remediation TS
Patrick Air Force Base, Florida

**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

3.3 SITE GEOLOGY AND HYDROGEOLOGY

Characterization of the vadose zone and shallow aquifer system at Site ST-29 was the objective of a previous site investigation. ESE (1991) installed eight soil boreholes and six monitoring wells in the immediate vicinity of the BX Service Station.

3.3.1 Lithology and Stratigraphic Relationships

Logs for boreholes and wells installed by ESE (1991) indicate that near-surface deposits consist of Holocene- and Pleistocene-age, fine- to coarse-grained marine sand that is poorly to moderately sorted and contains up to 40 percent shell fragments. These sand deposits extend to a depth of approximately 25 feet and contain interspersed organic matter. In some locations, the sand is stained dark gray and black from petroleum constituents. Soil borehole samples exhibited organic vapor readings ranging from background levels to greater than 200 ppmv.

The Anastasia Formation is discontinuous in this area and apparently was not encountered in boreholes installed by ESE at Site ST-29. A unit of the Caloosahatchee Marl formation was reportedly encountered at a depth of 25 feet below ground surface (bgs) in PPOL2-6 (ESE, 1991). Below 25 feet bgs, the soil was blue-gray, dense, moderately well-sorted fine- to medium grained silty sand with 5 to 65 percent shell fragments. Organic matter was dispersed throughout this unit, occasionally occurring in thin beds approximately 0.25-foot thick.

Below 51 feet in PPOL2-6, the Caloosahatchee Formation is a clay marl. As observed in this well, the unit is a blue-gray to dark-green clay marl layer with shell and limestone fragments. No soil discoloration or organic vapor readings above background were noted in these soils. The clay marl encountered in PPOL2-6 was observed from 51 feet bgs to at least 57 feet bgs. The clay marl reportedly correlates with a discontinuous, semiconfining clayey sand and silt unit within the Caloosahatchee Marl. The clayey unit has been encountered at Patrick AFB during other investigations, but the extent and thickness of the deposit has not been fully documented (ESE, 1991).

CPT data collected by ARA and Parsons ES in March 1994 indicate that deposits from the ground surface to approximately 20 feet bgs generally consist of sand and gravelly sand. Field observations by Parsons ES personnel indicate that the upper 2 to 4 feet of soil is fill, underlain in some locations by a thin layer of decayed organic material. The fill is reportedly material dredged from the Banana River and graded to level the Base area and raise it above marshy or wetland areas. Based on the CPT logs, the fill generally appears as gravelly sand or poorly sorted sand.

Native sand units are generally well sorted with some intervals of poorly sorted sand. Given the available information on the local geology, it is likely that the much of the soil indicated by CPT to be gravelly sand is actually sand with shell material. In some locations, visual inspection of soil samples collected near the water table indicated the presence of a thin, organic-rich layer. This layer is not distinguishable using the CPT logs, and is likely soil or vegetation that was buried when the site was filled.

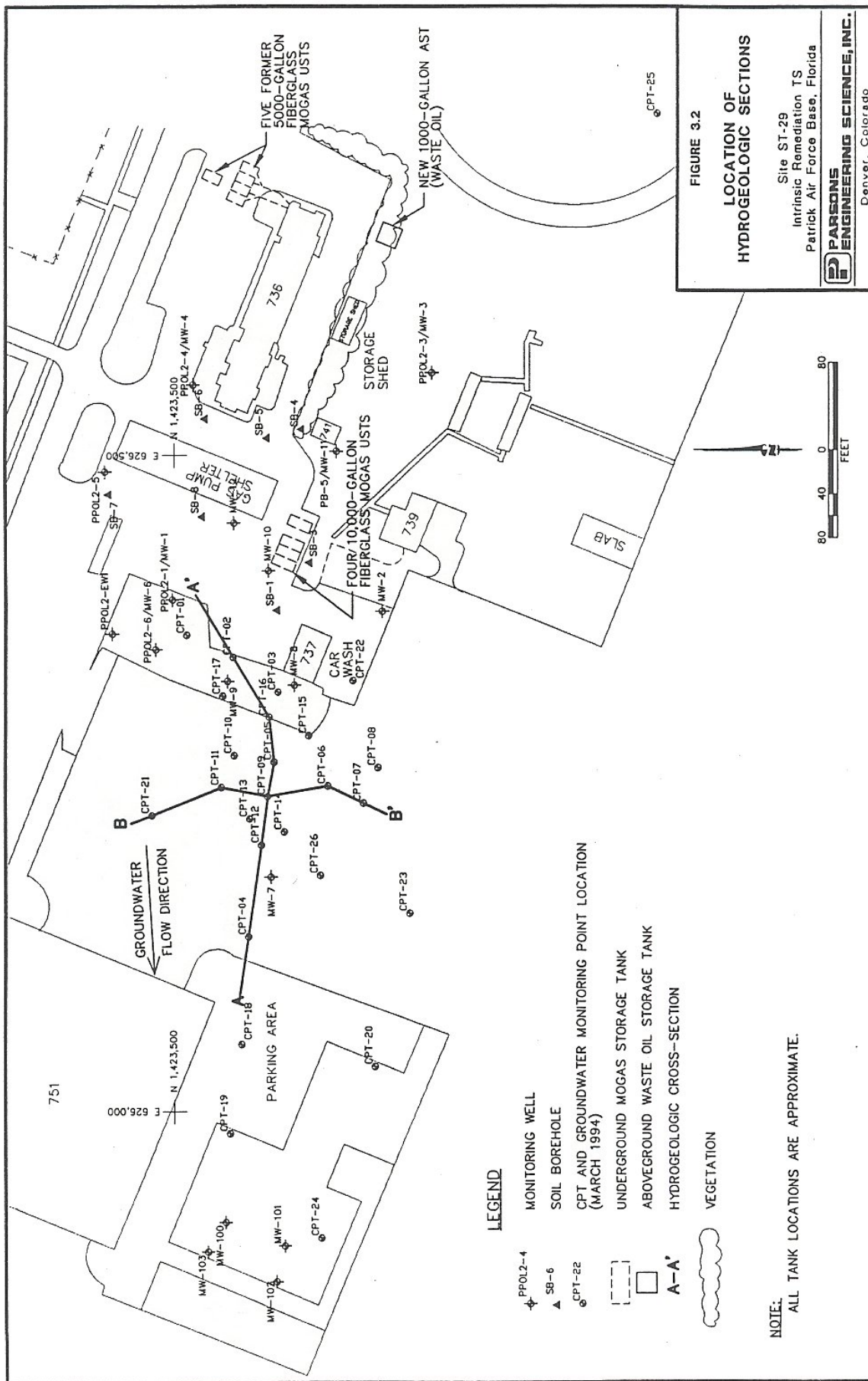
A body of silty clay and/or clayey silt was detected below 11 to 13 feet bgs in the vicinity of CPT locations CPT-05, CPT-06, CPT-08, CPT-09, and CPT-13. The exact geometry of the silt and clay unit is uncertain, but it appears to be of limited horizontal extent, pinching out north of CPT-13 and possibly pinching out south of CPT-08. Thickness of this unit appears to range up to at least 8 feet. The presence of these fine-grained deposits may indicate that the Anastasia Formation is present, but it is more likely that they represent a small, localized lens of fine material. Figure 3.2 shows the locations of cross-sections constructed using the geologic information gathered through CPT. Figure 3.3 shows cross-section A - A', oriented parallel to the direction of groundwater flow. Cross-section B - B', which is oriented perpendicular to groundwater flow, is presented as Figure 3.4.

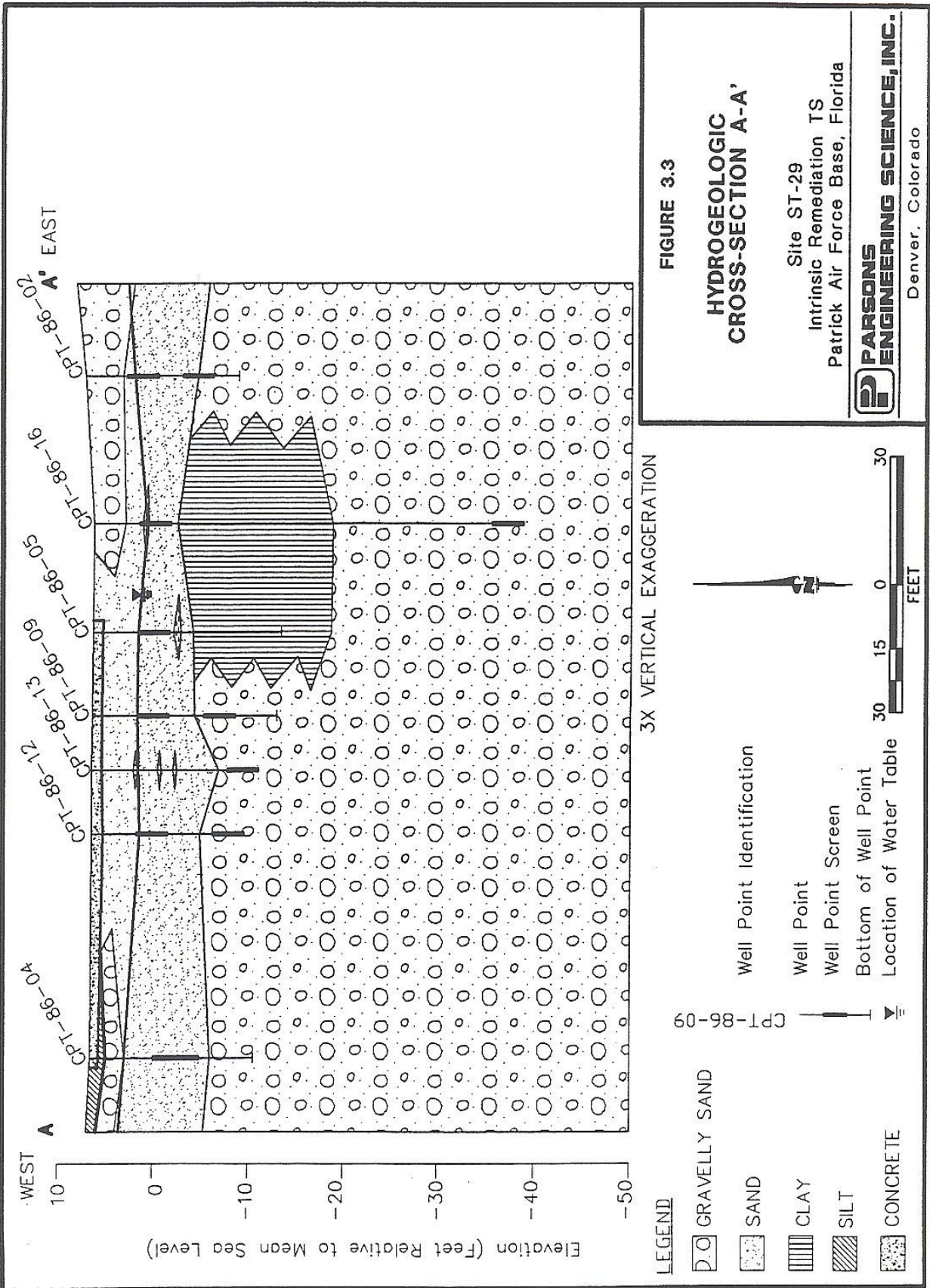
3.3.2 Groundwater Hydraulics

3.3.2.1 Flow Direction and Gradient

Shallow groundwater at Site ST-29 is present at depths of 4 to 5 feet bgs. Based on available hydrogeologic data, this shallow aquifer is unconfined. Historic groundwater elevation data for existing wells indicate that flow in the Site ST-29 area is generally to the west (ESE, 1991). Groundwater elevation data collected in March 1994 is presented in Table 3.1. Figure 3.5 shows the configuration of the shallow groundwater surface in the vicinity of Site ST-29 in March 1994. As indicated on Figure 3.5, the overall groundwater flow direction is to the west, toward the Banana River. The available data suggest that the flow in the site vicinity converges from the north and south in a relative low area from which flow is then to the west.

Water level data from CPT-25 indicate that a groundwater divide is present in the vicinity of Building 736. The groundwater elevation measured at CPT-25 (south and east of Building 736) was 0.78 foot above msl, while the measurement, at CPT-22 (just south of Building 737), was





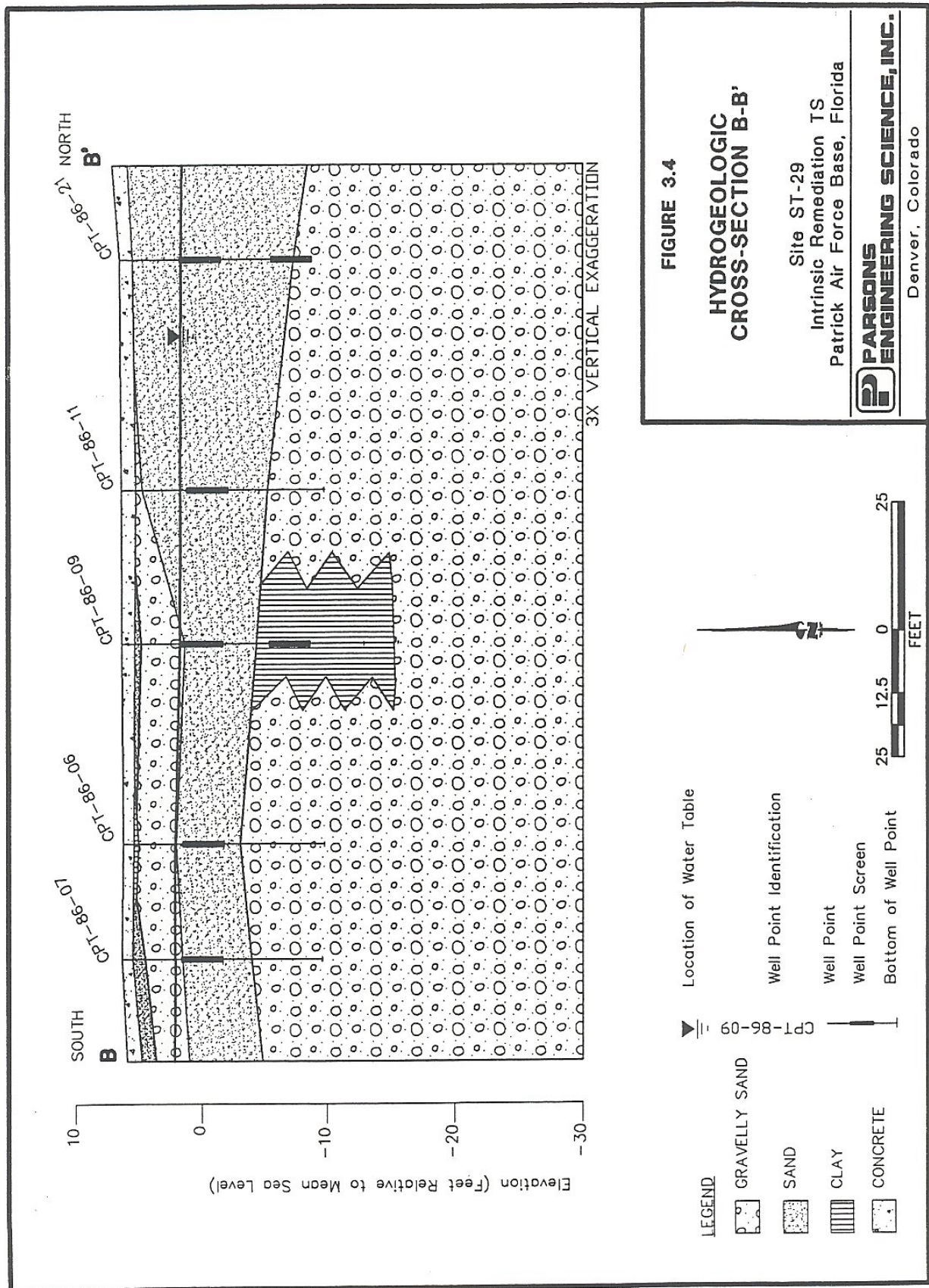


TABLE 3.1

**WATER LEVEL ELEVATION DATA
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA**

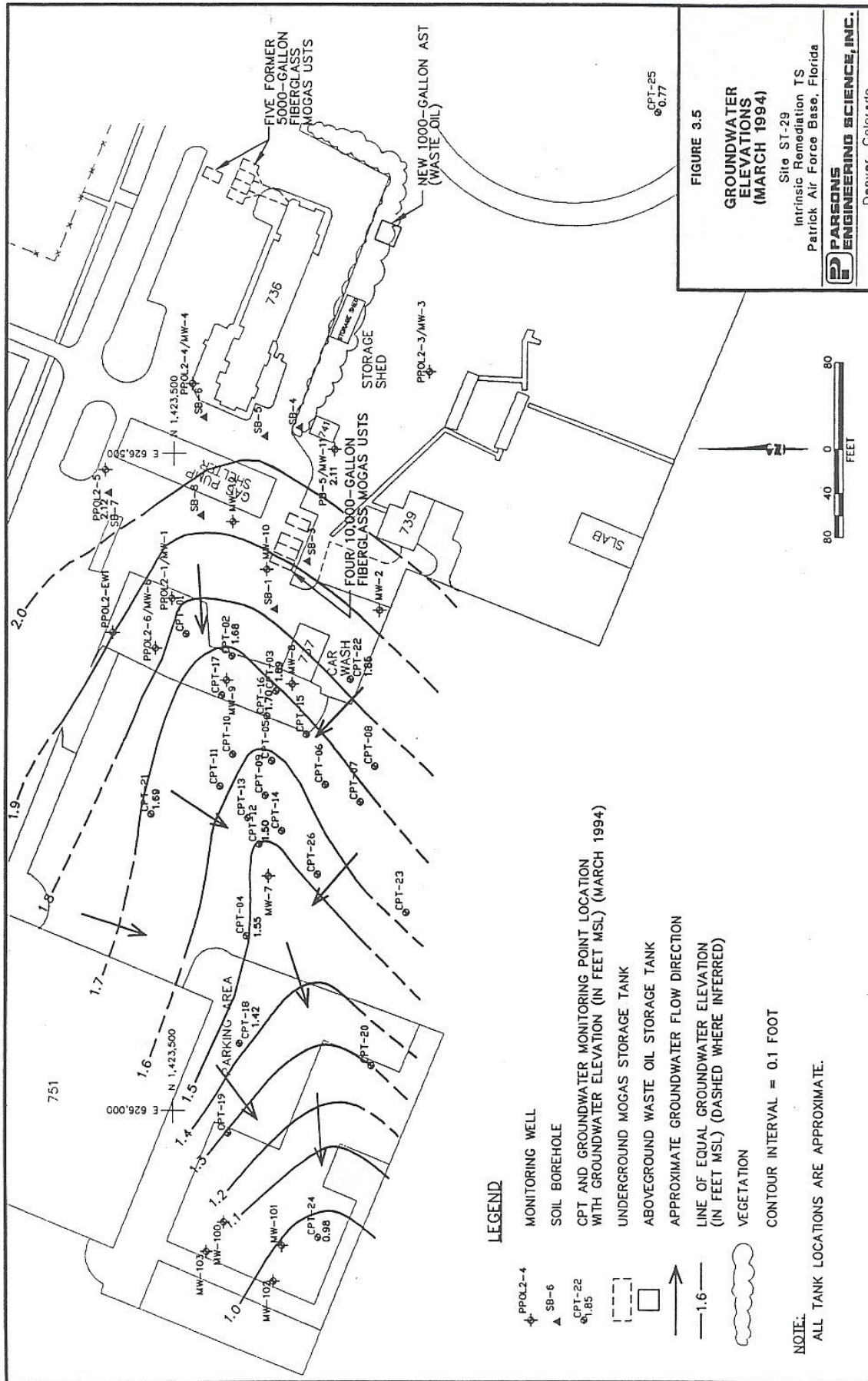
Sample Location	Sample Date	Easting	Northing	Datum ^{a/} Elevation (ft msl)	Ground Elevation (ft msl)	Total Depth (ft btoc)	Depth to Water (ft btoc)	Water Elevation (ft msl)
CPT-02S	3/27/94	1423346	626455	6.61	7.07	7.58	4.93	1.68
CPT-03D	3/27/94	1423319	626420	6.23	6.55	19.13	4.59	1.64
CPT-03S	3/27/94	1423319	626420	6.26	6.55	7.90	4.57	1.69
CPT-04D	3/27/94	1423133	626443	6.01	6.57	11.36	4.46	1.55
CPT-04S	3/27/94	1423133	626443	5.99	6.57	NR ^{b/}	4.46	1.53
CPT-09S	3/27/94	1423240	626428	6.13	6.35	7.76	4.35	1.78 ^{c/}
CPT-12S	3/27/94	1423203	626433	5.90	6.43	7.56	4.40	1.50
CPT-18S	3/27/94	1423051	626448	6.11	6.58	7.40	4.69	1.42
CPT-22D	3/27/94	1423328	626362	6.32	6.75	9.77	4.49	1.83
CPT-22S	3/27/94	1423328	626362	6.35	6.75	7.50	4.50	1.85
CPT-23D	3/27/94	1423151	626319	5.84	6.57	12.70	4.20	1.64
CPT-23S	3/27/94	1423151	626319	5.94	6.57	6.31	4.30	1.64
CPT-24D	3/27/94	1422903	626386	5.44	5.89	12.49	4.46	0.98
CPT-24S	3/27/94	1422903	626386	5.49	5.89	6.06	4.52	0.97
CPT-25D	3/27/94	1423761	626129	6.49	6.60	12.72	5.72	0.77
CPT-25S	3/27/94	1423761	626129	6.43	6.60	6.31	5.66	0.77
CPT-26D	3/27/94	1423180	626387	5.79	6.47	12.73	4.13	1.66
CPT-26S	3/27/94	1423180	626387	5.89	6.47	6.29	4.25	1.64 ^{c/}
PB5	3/23/94	NA ^{d/}	NA	10.86	7.39	15.45	8.75	2.11
PPOL2-1	3/25/94	1423390	626502	7.47	6.92	NA	5.33	2.14
PPOL2-5	3/25/94	NA	NA	7.48	NA	12.51	5.36	2.12
PPOL2-6	3/25/94	1423352	626515	6.64	6.39	NA	4.93	1.71

^{a/} Datum is top of well casing.

^{b/} NR = No Reading.

^{c/} Data are suspect.

^{d/} NA = Not available.



1.85 feet above msl, suggesting a southeasterly or easterly flow direction east of Building 736. The presence of a divide in this area is also supported by previous data from wells PPOL2-1 through PPOL2-6, which indicate groundwater flow in the area of the service station is to the west. Additional water level elevation data collected in 1994 (but not concurrent with the data from the CPT points) also confirms that the divide exists, likely to the east of wells PPOL2-4 and PPOL2-3 (CH2M Hill, 1994).

Previous data indicated that the horizontal hydraulic gradient at the site ranges from 0.00096 to 0.003 foot per foot (ft/ft) (ESE, 1991; O'Brien and Gere Engineers, Inc., 1992). Water level measurements made by Parsons ES in March 1994 also indicate that the local hydraulic gradient is approximately 0.002 ft/ft. Given the distance to the Banana River (2,400 feet) and the water level elevations observed at the site (1 to 2 feet above msl), it is likely that the gradient diminishes to the west. If the observed gradient (0.002) extended all the way to the Banana River, the water table would be 2 to 3 feet below msl at the Banana River.

Vertical hydraulic gradients measured in monitoring point nests range from 0.000 ft/ft (i.e., no vertical gradient) at CPT-23 to 0.003 ft/ft (downward) at CPT-03 and CPT-22. There is no evidence of upward gradients within the shallow aquifer at this site, which is consistent with the proximity of the area to a groundwater divide. In typical groundwater flow systems, the vertical component of flow is downward in the vicinity of a divergent groundwater divide. Vertical gradients typically decrease or flatten out away from the divergent divide, eventually turning upward in the vicinity of groundwater discharge areas or convergent groundwater divides. It appears that the local flow system exhibits a pattern similar to this description. Downward vertical gradients were observed at CPT-03 and CPT-22, which are closer to the divide than most other nests. Further downgradient from the divide, such as at CPT-23, the vertical gradient diminishes. The apparent discharge area for the local western groundwater flow component is the Banana River, and it is likely that vertical gradients nearer the river are directed upward. On the eastern side of the divide, groundwater flow discharges to the Atlantic Ocean.

3.3.2.2 Hydraulic Conductivity

No previous slug test data are available for the site. ESE (1991) estimated average hydraulic conductivity (K) in the ST-29 area to be 0.26 foot per minute (ft/min), based on data gathered in other areas of Patrick AFB and the assumption that the soil lithologies throughout Patrick AFB are relatively similar (ESE, 1991). Rising head slug tests were conducted by Parsons ES in March

1994 according to methods mentioned in Section 2. Results of these tests suggest that the hydraulic conductivity of the shallow portion of the aquifer is in the range of 0.023 to 0.089 h/min, with an average K of approximately 0.052 ft/min, or 0.026 centimeter per second (cm/sec). Slug test results are summarized in Table 3.2.

TABLE 3.2
SLUG TEST RESULTS
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

WELL	TEST	HYDRAULIC CONDUCTIVITY (feet/minute)	HYDRAULIC CONDUCTIVITY (cm/sec)
PPOL2-1	Rising Head #2	0.023	0.012
PPOL2-4	Rising Head #1	0.064	0.032
PPOL2-4	Rising Head #2	0.089	0.045
PPOL2-5	Rising Head #1	0.031	0.016
PPOL2-5	Rising Head #2	0.025	0.013
PPOL2-6	Rising Head #1	0.096	0.049
	AVERAGE*	0.052	0.026

* Average of wells PPOL2-1, PPOL2-4, and PPOL2-5.
Well PPOL2-6 completed near base of shallow aquifer.

3.3.2.3 Effective Porosity(n_e)

Because of the difficulty involved in accurately determining effective porosity, accepted literature values for the type of soil comprising the shallow saturated zone were used. Freeze and Cherry (1979) give a range of effective porosity for sand and/or gravel of 0.25 to 0.50. The effective porosity for sediments of the shallow saturated zone was initially assumed to be 0.35 for calculating the advective groundwater velocity.

3.3.2.4 Advective Groundwater Velocity (v)

The advective velocity of groundwater in the direction parallel to groundwater flow is given by:

$$v = \frac{-K \, dH}{n_e \, dL}$$

Where: v = Average advective groundwater velocity (seepage velocity) [L/T]

K = Hydraulic conductivity [L/T]

dH/dL = Gradient [L/L]

n_e = Effective porosity.

Using this relationship in conjunction with site-specific gradient (0.002 ft/ft) and hydraulic conductivity (0.052 ft/min) data, the average advective groundwater velocity at the site can be calculated. Because effective porosity was not measured at the site, velocity calculations were performed for the assumed value of 0.35, as well as for 0.25 and 0.50, which define the limits of the range indicated by Freeze and Cherry (1979).

Using an effective porosity of 0.35, the average advective groundwater velocity is 0.43 foot per day (ft/day) or approximately 156 ft/year. Using effective porosity values of 0.25 and 0.50 yields velocities of 0.6 ft/day and 0.3 ft/day, respectively (220 ft/yr and 110 ft/yr, respectively).

3.3.2.5 Preferential Flow Paths

One preferential contaminant migration pathway was identified during the field work phase of this project. This pathway is a storm sewer located just west of the car wash area. This storm sewer runs northeast-southwest, 6 feet west of and roughly parallel to the western edge of the car wash building.

The influence of this corridor on contaminant migration has not been directly investigated. However, during field work conducted by Parsons ES and RSKERL personnel in March 1994, some visual observations were made. Access to the sewer was limited by heavy steel grates that could not readily be removed, so observations were made through the grates. It appeared that the storm sewer piping is made of concrete and did not contain moving water, although the base of the pipe may be deep enough to be near the water table. Puddles of standing water were present in the piping, but no petroleum sheen or odor was observed.

Because of the relatively high hydraulic conductivity of the shallow saturated zone and the nature of storm sewer construction (concrete), it is unlikely that this drain has a significant impact on groundwater flow at the site, unless preferential flow occurs through the backfill envelope surrounding the sewer. Further investigation of this occurrence was not possible at the time the observations were made. However, water level and BTEX data from CPT points installed near the sewer suggest that there is no groundwater flow or contaminant migration parallel to the sewer line. The BTEX plume described in Section 4 appears to pass beneath the storm sewer without redirection.

3.3.4 Groundwater Use

Groundwater from the unconsolidated surficial deposits at Patrick AFB is not extracted for any use. Water is obtained from the City of Cocoa Beach, with the City of Melbourne, Florida providing supplemental water if necessary. Patrick AFB maintains five standby water supply wells, primarily for fire suppression use. These wells are screened in Ocala Formation limestones that are part of the confined Floridan Aquifer.

3.4 CLIMATOLOGICAL CHARACTERISTICS

The climate of the barrier island is humid subtropical. Monthly mean high temperatures range from 69 degrees Fahrenheit (°F) in January to 87°F in July and August. Extreme high and low temperatures for the period from 1950 to 1980 were 99°F and 27°F, respectively.

Rainfall is unevenly distributed throughout the year, with the period from June through October having distinctly more precipitation than the rest of the year. A 30-year (1950 to 1980) mean of the annual precipitation recorded at Patrick AFB is 44.7 inches, and the mean annual evapotranspiration is 40.3 inches (ESE, 1991). Based on these data, an average of 4.4 inches of precipitation is available to infiltrate through surface soils and recharge groundwater on an annual basis.

SECTION 4

NATURE AND EXTENT OF CONTAMINATION AND SOIL AND GROUNDWATER GEOCHEMISTRY

4.1 SOURCE OF CONTAMINATION

The former 10,000-gallon MOGAS UST and the product lines that were discovered to be leaking in 1986 were apparently the sources of contamination at Site ST-29. It was estimated that 700 gallons of product was released between 1985, when the tanks were installed, and 1986, when the leaking UST was removed and the line was presumably repaired. Records describing activities to mitigate the leaks and remediate soil at that time were not available during preparation of this report. Data from previous investigations (ESE, 1991; ES, 1993) indicate that soil contamination is concentrated in the areas near and downgradient from the 10,000-gallon MOGAS USTs, north of the car wash (Building 737, Figure 3.5).

4.2 SOIL CHEMISTRY

4.2.1 Residual Contamination

Residual light nonaqueous-phase liquid (LNAPL) is defined as the LNAPL that is trapped in the aquifer by the processes of cohesion and capillarity, and therefore will not flow within the aquifer and will not flow from the aquifer matrix into a well under the influence of gravity. Mobile LNAPL (i.e., free product) is defined as the LNAPL that is free to flow in the aquifer and that will flow from the aquifer matrix into a well under the influence of gravity. Mobile LNAPL has not been detected in monitoring wells or monitoring points at Site ST-29. Observations made during installation of a bioventing unit northeast of the car wash suggest that significant contamination was present, with the soil reportedly saturated with fuel hydrocarbons (ES, 1993). The following sections describe the residual LNAPL contamination found at Site ST-29.

4.2.1.1 Soil BTEX Contamination

Residual BTEX contamination resulting from vertical and lateral migration of mobile LNAPL and dissolved hydrocarbons is found over a wide area at Site ST-29. Table 4.1 contains soil BTEX data. Figure 4.1 shows the extent of contaminated soil indicated by LIF data and laboratory analytical results. Soil BTEX contamination appears to extend at least to CPT-O9, approximately 220 feet downgradient from the source area. The zone of contaminated soil is approximately 90 feet wide at its widest point.

LIF data collected during CPT activities suggest that hydrocarbon contamination is present in the vicinity of points CPT-02, CPT-03, CPT-O9, and possibly CPT-10. LIF profiles (Gildea *et al.*, 1994) suggest the presence of hydrocarbons at or slightly above the water table in these locations. It appears that the hydrocarbons detected by LIF are residual LNAPL and not mobile LNAPL, because monitoring points installed at the water table in the same locations did not contain free product. These detections may represent dissolved contamination carried into the unsaturated zone during a period of elevated groundwater levels or the remains of a smear zone created as a thin layer of free product migrated laterally with groundwater flow and was introduced to the soil as the water table fluctuated.

The highest observed concentration of residual total BTEX is 1,236.07 milligrams per kilogram (mg/kg) in a soil sample taken from 6 feet bgs at CPT-02, which is about 120 feet west-northwest of the suspected source of hydrocarbon contamination (Figure 4.1). A total BTEX concentration of 974.83 mg/kg was detected at 5.5 feet bgs at CPT-03, which is directly downgradient from the source area. At CPT-02 and CPT-03, the highest concentrations were in the vicinity of the water table (e.g., 5.5 to 6 feet bgs). In both locations, concentrations are generally an order of magnitude lower within 1 foot above and below the highest concentrations, and another order of magnitude lower 2 feet above and below the interval with the greatest contamination. Samples collected from CPT-05, CPT-O9, CPT-13, and CPT-15 also contained BTEX compounds, but at total concentrations below 0.1 mg/kg (Table 4.1).

Benzene was detected in samples from CPT-02 and CPT-03 in concentrations ranging from 0.164 to 6.99 mg/kg. Benzene also was detected in one sample from CPT-16 at a concentration of 0.00752 mg/kg. These locations are downgradient from the main source area; in the source area, benzene was not detected in soil or soil gas samples collected

TABLE 4.1

**FUEL HYDROCARBON COMPOUNDS DETECTED IN SOIL
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA**

Sample Location	Depth (ft bgs)	Benzene (mg/kg)	Toluene (mg/kg)	Ethylbenzene (mg/kg)	p-Xylene (mg/kg)	m-Xylene (mg/kg)	o-Xylene (mg/kg)	Total Xylenes (mg/kg)	Total BTEX (mg/kg)	1,3,5-TMB (mg/kg)	1,2,4-TMB (mg/kg)	1,2,3-TMB (mg/kg)	TPH ^a (mg/kg)
CPT-02-A17	4	BLQ ^b	BLQ	0.0345	0.0249	0.054	0.0296	0.1085	0.143	0.018	0.0514	0.017	ND ^c
CPT-02-A18	5	0.197	0.0605	0.514	1.44	0.976	0.703	3.119	3.8905	3.1	3.28	2.65	140
CPT-02-A19	6	6.99	8.08	191	257	542	231	1030	1236.07	274	786	180	17100
CPT-02-A20	6.45	0.68	0.345	16.1	20.3	45.9	17.9	84.1	101.225	26	77.4	17.5	1660
CPT-02-A21	7	0.339	0.106	2.26	2.91	6.77	2.74	12.42	15.125	3.75	11.7	2.59	289
CPT-03-A22	3	0.164	0.0142	0.21	0.253	0.523	0.243	1.019	1.4072	0.319	0.844	0.227	20.9
CPT-03-A23	4.5	ND	BLQ	0.00838	0.0102	0.0209	0.0107	0.0418	0.05018	0.0155	0.0461	0.013	0.2
CPT-03-A24	5.5	BLQ	0.462	BLQ	39.8	45.7	85.8	171.3	171.762	253	332	123	11700
CPT-03-A25	6.5	2.33	29.5	120	186	428	209	823	974.83	181	675	124	9300
CPT-03-A26	7	0.366	0.532	2.02	3.48	7.58	4.4	15.46	18.378	3.97	12.7	2.87	287
CPT-5-A1	3.5	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.00746	BLQ	ND
CPT-5-A2	4.5	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.0117	BLQ	ND
CPT-5-A3	5	BLQ	BLQ	BLQ	0.00725	BLQ	BLQ	0.00725	0.00725	BLQ	0.00879	BLQ	ND
CPT-5-A4	5.5	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.0149	BLQ	ND
CPT-9-A4	2.5	BLQ	BLQ	ND	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	ND	ND	2
CPT-9-A5	4.5	BLQ	BLQ	BLQ	BLQ	BLQ	ND	BLQ	BLQ	BLQ	BLQ	BLQ	47.1
CPT-9-A6	5	BLQ	0.034	BLQ	0.0311	0.0229	0.0109	0.0649	0.0989	0.0121	BLQ	0.00976	2740
CPT-9-A7	6	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.00818	BLQ	15.2
CPT-13	5.5	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	ND
CPT-15-A8	3	BLQ	BLQ	ND	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.016	BLQ	ND
CPT-15-A9	4	BLQ	BLQ	ND	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.0128	BLQ	0.01
CPT-15-A10	5	BLQ	0.012	0.00978	BLQ	BLQ	0.0226	0.0226	0.04438	BLQ	0.0114	BLQ	526
CPT-15-A11	5.5	ND	ND	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.0179	BLQ	ND
CPT-16-A1	4.5	0.00752	0.00761	BLQ	BLQ	BLQ	BLQ	BLQ	0.01513	BLQ	0.00658	BLQ	0.04
CPT-16-A2	6	ND	BLQ	ND	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.0104	BLQ	ND
CPT-17-A12	2	ND	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.0127	BLQ	ND
CPT-17-A13	3	ND	BLQ	ND	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.0248	BLQ	ND
CPT-17-A14	4	ND	BLQ	BLQ	BLQ	0.00779	BLQ	0.00779	0.00779	BLQ	0.0176	BLQ	ND
CPT-17-A15	5	ND	BLQ	ND	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	0.0172	BLQ	ND

^a TPH = Total petroleum hydrocarbons (quantified with a JP-4 standard).

^b BLQ = Below limit of quantitation, or <0.02 mg/kg.

^c ND = Not detected

during installation and evaluation of the bioventing system. Total BTEX concentrations of 2,816 mg/kg were detected in soils during installation of the horizontal bioventing test well (ES, 1993 and 1994a).

4.2.1.2 Soil TPH Contamination

Total petroleum hydrocarbons (TPH) were detected in nearly all of the locations where BTEX compounds were detected. Table 4.1 presents the soil TPH data. All locations where TPH were detected are located within the shaded area shown on Figure 4.1, although TPH concentrations are not indicated on this figure. The USEPA laboratory quantified TPH concentrations by comparison to a JP-4 standard, while the source of contamination is MOGAS, which is composed of larger fractions of lighter hydrocarbons (e.g., the BTEX compounds). While there is a possibility that this could bias the TPH concentrations below those measured against a gasoline-based standard, it does not appear to present a problem at this site. In most locations where both TPH and BTEX compounds were detected, TPH concentrations are at least 10 times the BTEX concentrations. In addition, it is likely that the residual product in the soil is weathered, and that the fraction of BTEX has diminished such that the remaining fraction is largely comprised of heavier gasoline hydrocarbons, such as those that comprise a large fraction of JP-4. In addition, TPH data were collected only to provide additional information on the nature and extent of hydrocarbon contamination.

4.2.2 Total Organic Carbon

TOC concentrations are used to estimate the amount of organic matter sorbed on soil particles or trapped in the interstitial passages of a soil matrix. The TOC concentration in the saturated zone is an important parameter used to estimate the amount of contaminant that could potentially be sorbed to the aquifer matrix. Sorption results in retardation of the contaminant plume relative to the average advective groundwater velocity. Measurements of TOC were taken from core samples obtained from several CPT locations. TOC in the soil at this site ranges from 0.016 to 1.86 percent (Table 4.2). Some of the highest values are from samples that also contained significant concentrations of BTEX compounds. However, TOC concentrations are high in some samples because of organic matter.

TABLE 4.2
SOIL TOTAL ORGANIC CARBON RESULTS
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Sample Location	Sample Number	Depth (feet bgs)	% Total Organic Carbon (mean \pm SD) ^{a/}
CPT-02	86-02-A17	4.0	0.016 \pm 0.002
CPT-02	86-02-A18	5.0	0.707 \pm 0.022
CPT-02	86-02-A19	6.0	0.166 \pm 0.022
CPT-02	86-02-A20	6.5	0.089 \pm 0.015
CPT-02	86-02-A21	7.0	0.158 \pm 0.034
CPT-03	86-03-A22	3.0	0.189 \pm 0.068
CPT-03	86-03-A23	4.5	0.087 \pm 0.008
CPT-03	86-03-A24	5.5	0.373 \pm 0.030
CPT-03	86-03-A25	6.5	0.111 \pm 0.020
CPT-03	86-03-A26	7.0	0.182 \pm 0.040
CPT-05	86-05-A1	3.5	0.028 \pm 0.001
CPT-05	86-05-A2	4.5	0.065 \pm 0.002
CPT-05	86-05-A3	5.0	0.334 \pm 0.003
CPT-05	86-05-A4	5.5	1.260 \pm 0.220
CPT-09	86-09-A4	2.5	0.036 \pm 0.003
CPT-09	86-09-A5	4.5	0.042 \pm 0.006
CPT-09	86-09-A6	5.0	0.307 \pm 0.015
CPT-09	86-09-A7	6.0	1.860 \pm 0.083
CPT-13	86-13-SS1-A16	5.5	1.050 \pm 0.077
CPT-15	86-15-A8	3.0	0.031 \pm 0.001
CPT-15	86-15-A9	4.0	0.053 \pm 0.003
CPT-15	86-15-A10	5.0	1.130 \pm 0.030
CPT-15	86-15-A11	5.5	0.558 \pm 0.044
CPT-16	86-16-A1	4.5	0.580 \pm 0.029
CPT-16	86-16-A2	6.0	0.441 \pm 0.010
CPT-17	86-17-A12	2.0	0.026 \pm 0.001
CPT-17	86-17-A13	3.0	0.034 \pm 0.001
CPT-17	86-17-A14	4.0	0.294 \pm 0.009
CPT-17	86-17-A15	5.0	0.379 \pm 0.016

a/ SD = Standard Deviation.

4.3 GROUNDWATER CHEMISTRY

4.3.1 Dissolved Contamination

Laboratory analytical results for groundwater samples collected during previous site investigations indicated the presence of fuel-hydrocarbon contamination in the shallow saturated zone in the vicinity of Site ST-29. Groundwater samples collected in March 1994 by Parsons ES and RSKERL personnel, by RSKERL personnel in March 1995, and by CH2M Hill in May 1995, confirmed these results. Table 4.3 summarizes groundwater contaminant data for March 1994. Table 4.4 summarizes groundwater contaminant data for March and May 1995.

During March 1994 sampling activities, Parsons ES and RSKERL personnel noted that the groundwater in the site vicinity often displayed unusual odors or characteristics. For example, water from existing wells MW-100 through MW-103, locations downgradient from the site near Building 751, appeared sudsy, as if soap or a surfactant were present. In addition, water from locations nearer the service station (e.g., CPT-05) had an odor similar to sulfur.

Figure 4.2 is an isopleth map that shows the distribution of total BTEX dissolved in groundwater in March 1994. Isopleths are drawn based on the maximum concentration detected at any of the sample depths at each location. Figure 4.3 is a vertical profile through the plume, showing the vertical distribution of contamination in March 1994. Figure 4.4 is an isopleth map that shows the distribution of total BTEX dissolved in groundwater in March and May 1995. Isopleths are drawn based on the maximum concentration detected at each location.

4.3.2 Documented Loss of Contaminants at the Field Scale

As noted in Section 1, the documented loss of contaminants at the field scale is the first of three lines of evidence that can be used to document the occurrence of intrinsic remediation. The data presented below provide strong evidence of the loss of contaminant mass at Site ST-29.

Dissolved BTEX contamination is migrating to the west in the direction of groundwater flow. As defined by the 5-microgram-per-liter (11g/L) total BTEX isopleth

TABLE 4.3

FUEL HYDROCARBON COMPOUNDS DETECTED IN GROUNDWATER, MARCH 1994
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Sample Location	Sample Number	Sample Date	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	p-Xylene (µg/L)	m-Xylene (µg/L)	o-Xylene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	1,3,5-TMB (µg/L)	1,2,4-TMB (µg/L)	1,2,3-TMB (µg/L)
CPT-01	CPT-86-001	3-23-94	BLQ ^v	2.42	BLQ	BLQ	BLQ	BLQ	BLQ	2.42	BLQ	BLQ	BLQ
CPT-02S	CPT-86-002S	3-23-94	375	18.9	165	166	353	119	638	1196.9	71.2	NA ^w	86.3
CPT-02D	CPT-86-002D	3-23-94	1.5	1.7	1.1	1.4	2.6	1.4	5.4	9.7	BLQ	NA	1.3
CPT-03S	CPT-86-003S	3-23-94	724	737	823	1220	2410	1390	5020	7304	347	NA	403
CPT-03M	CPT-86-003M	3-23-94	207	15.6	40.5	42.2	24	7.5	73.7	336.8	2.8	NA	16
CPT-03D	CPT-86-003D	3-23-94	1.8	1.1	BLQ	BLQ	1.4	BLQ	1.4	4.3	BLQ	NA	BLQ
CPT-04S	CPT-86-004S	3-23-94	BLQ	6	BLQ	BLQ	BLQ	BLQ	BLQ	6	BLQ	BLQ	BLQ
CPT-04D	CPT-86-004D	3-25-94	BLQ	3.7	BLQ	BLQ	BLQ	BLQ	BLQ	3.7	BLQ	BLQ	BLQ
CPT-05S	CPT-86-005S	3-25-94	BLQ	1.2	BLQ	BLQ	BLQ	BLQ	BLQ	1.2	BLQ	NA	BLQ
CPT-06S	CPT-86-006S	3-25-94	BLQ	11.1	BLQ	1.3	2.3	BLQ	3.6	14.7	BLQ	NA	BLQ
CPT-07S	CPT-86-007S	3-25-94	BLQ	3.9	BLQ	BLQ	1	BLQ	1	4.9	BLQ	NA	BLQ
CPT-08S	CPT-86-008S	3-25-94	BLQ	2.8	BLQ	BLQ	BLQ	BLQ	BLQ	2.8	BLQ	BLQ	BLQ
CPT-09S	CPT-86-009S	3-25-94	2	4	BLQ	BLQ	BLQ	BLQ	BLQ	6	BLQ	BLQ	BLQ
CPT-09D	CPT-86-009D	3-25-94	427	14.1	2.9	11.7	12.1	9.7	33.5	477.5	BLQ	NA	9.4
CPT-10S	CPT-86-010S	3-25-94	BLQ	3.1	BLQ	BLQ	BLQ	BLQ	BLQ	3.1	BLQ	BLQ	BLQ
CPT-11S	CPT-86-011S	3-25-94	BLQ	1	BLQ	BLQ	BLQ	BLQ	BLQ	1	BLQ	BLQ	BLQ
CPT-12S	CPT-86-012S	3-25-94	BLQ	1.1	BLQ	BLQ	1.2	BLQ	1.2	2.3	BLQ	NA	BLQ
CPT-12D	CPT-86-012D	3-25-94	93.5	5.9	BLQ	8.4	7	3.7	19.1	118.5	BLQ	NA	4.1
CPT-13S	CPT-86-013S	3-25-94	BLQ	8.4	BLQ	10.4	5.4	3.1	18.9	56.4	BLQ	NA	6.7
CPT-16S	CPT-86-016S	3-26-94	1	1.9	BLQ	BLQ	BLQ	BLQ	BLQ	2.9	BLQ	BLQ	BLQ
CPT-16DD	CPT-86-016DD	3-31-94	BLQ	1.9	BLQ	BLQ	BLQ	BLQ	BLQ	1.9	BLQ	BLQ	BLQ
CPT-18S	CPT-86-018S	3-24-94	BLQ	1.7	2.3	3.8	6.6	4	14.4	18.4	1.4	NA	1.6
CPT-18D	CPT-86-018D	3-24-94	8.3	2.1	BLQ	BLQ	BLQ	BLQ	BLQ	10.4	BLQ	BLQ	BLQ
CPT-18DD	CPT-86-018DD	3-31-94	BLQ	3.5	BLQ	BLQ	BLQ	BLQ	BLQ	3.5	BLQ	BLQ	BLQ
CPT-19S	CPT-86-019S	3-24-94	BLQ	BLQ	1.1	1.5	2.7	BLQ	4.2	5.3	BLQ	NA	BLQ
CPT-19D	CPT-86-019D	3-24-94	1.5	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	1.5	BLQ	BLQ	BLQ
CPT-20S	CPT-86-020S	3-24-94	BLQ	2.1	BLQ	1.5	2.7	1.8	6	8.1	BLQ	NA	1
CPT-20D	CPT-86-020D	3-24-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
CPT-21S	CPT-86-021S	3-25-94	NA	5.1	BLQ	BLQ	BLQ	BLQ	BLQ	5.1	BLQ	NA	BLQ
CPT-21D	CPT-86-021D	3-25-94	NA	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
CPT-22S	CPT-86-022S	3-26-94	NA	1.9	BLQ	BLQ	BLQ	BLQ	BLQ	1.9	BLQ	BLQ	BLQ
CPT-22D	CPT-86-022D	3-26-94	1.5	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	1.5	BLQ	BLQ	BLQ
CPT-23S	CPT-86-023S	3-25-94	BLQ	BLQ	BLQ	BLQ	1.7	BLQ	1.7	1.7	BLQ	NA	BLQ
CPT-23D	CPT-86-023D	3-25-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
CPT-24S	CPT-86-024S	3-26-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ

TABLE 4.3 (CONCLUDED)

FUEL HYDROCARBON COMPOUNDS DETECTED IN GROUNDWATER, MARCH 1994
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Sample Location	Sample Number	Sample Date	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	p-Xylene (µg/L)	m-Xylene (µg/L)	o-Xylene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	1,3,5-TMB (µg/L)	1,2,4-TMB (µg/L)	1,2,3-TMB (µg/L)
CPT-24D	CPT-86-024D	3-26-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
CPT-25S	CPT-86-025S	3-26-94	BLQ	2.1	2.3	4.1	6.9	3.5	14.5	18.9	1.7	NA	1.5
CPT-25D	CPT-86-025D	3-26-94	BLQ	1	BLQ	BLQ	1.4	BLQ	1.4	2.4	BLQ	NA	BLQ
CPT-26S	CPT-86-026S	3-26-94	BLQ	1.1	BLQ	BLQ	BLQ	BLQ	BLQ	1.1	BLQ	BLQ	BLQ
CPT-26D	CPT-86-026D	3-26-94	BLQ	1	BLQ	BLQ	BLQ	BLQ	BLQ	1	BLQ	BLQ	BLQ
CPT-14D	CPT-86-014D	3-25-94	960	16.6	11.5	39.2	36.8	44.2	120.2	1108.3	15.3	NA	23
MW-100	CPT-86-100	3-23-94	4.1	BLQ	BLQ	1.1	1	BLQ	2.1	6.2	BLQ	BLQ	BLQ
PH35	CPT-86-PH35	3-26-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
MW-101	CPT-86-101	3-23-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
MW-102	CPT-86-102	3-23-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
MW-103	CPT-86-103	3-23-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
PPOL2-6	CPT-86-PPOL2-6	3-26-94	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ	BLQ
PPOL2-1	CPT-86-PPOL2-1	3-26-94	BLQ	BLQ	BLQ	BLQ	1.4	BLQ	1.4	1.4	BLQ	BLQ	BLQ

^a BLQ = Below quantitation limit, or < 1 µg/L.

^b NA=Not available.

TABLE 4-4

FUEL HYDROCARBON COMPOUNDS DETECTED IN GROUNDWATER, MARCH AND MAY 1995
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

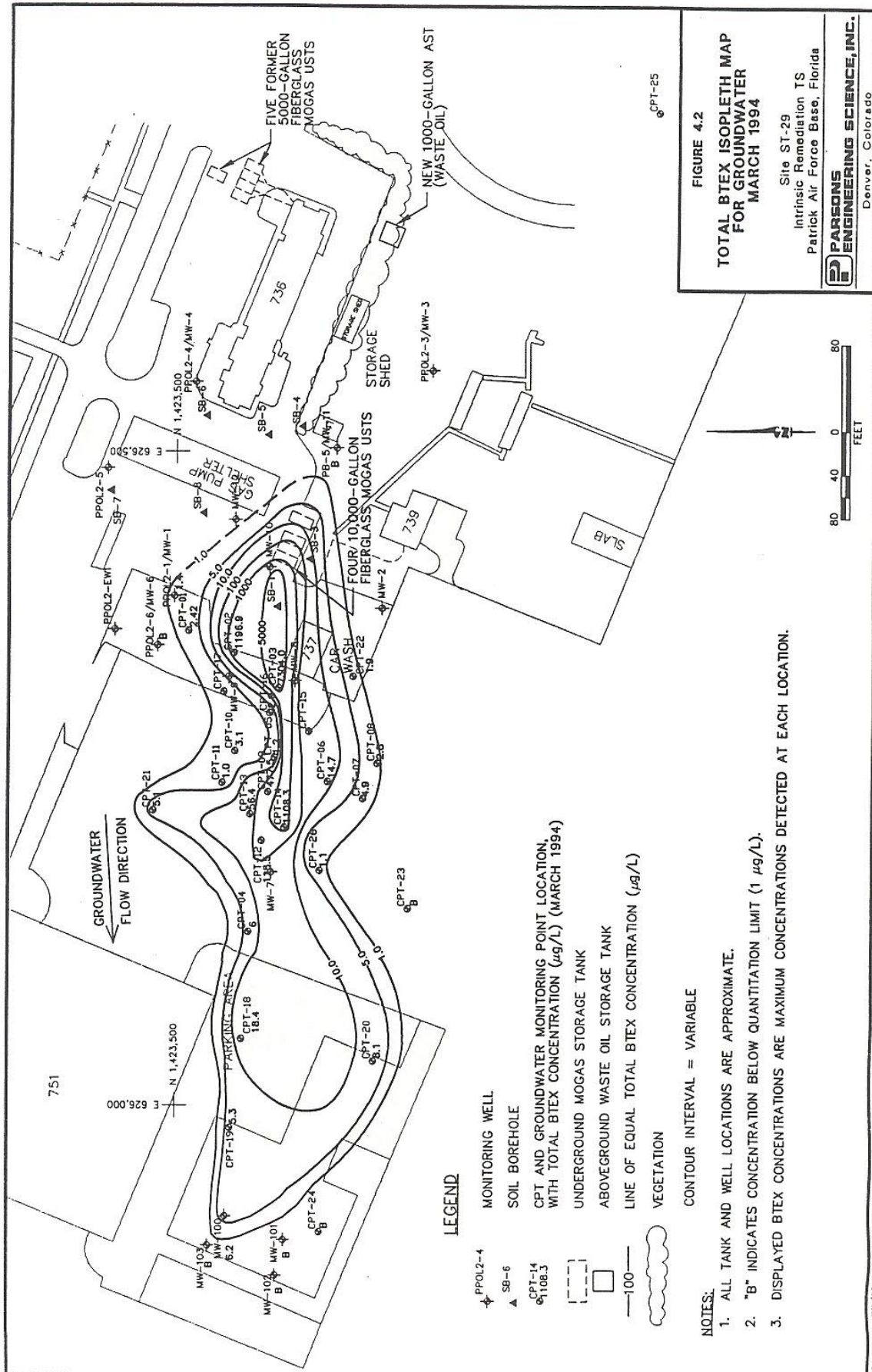
Sample Location	Sample Number	Sample Date	Benzene (µg/L)	Toluene (µg/L)	Ethylbenzene (µg/L)	p-Xylene (µg/L)	m-Xylene (µg/L)	o-Xylene (µg/L)	Total Xylene (µg/L)	Total BTX (µg/L)	1,3,5 TMB (µg/L)	1,2,4 TMB (µg/L)	1,2,3 TMB (µg/L)	Total TMB (µg/L)	TOC (mg/L)
CPT-02S	2S	3/23/95	167.29	6.25	132.59	95.65	156.04	8.58	260.27	566.4	43.95	203.4	89.18	336.53	14.9
CPT-02S	2S DUP	3/23/95	156.45	6.37	135.4	107.45	168.18	9.36	284.99	583.21	48	202.48	89.97	340.45	16.3
CPT-03D	3D	3/23/95	30.95	BLQ ^a	10.49	22.49	2.96	1.39	26.84	68.28	1.4	1.97	2.87	6.24	13.8
CPT-03D	3D DUP	3/23/95	30.31	0.99	10.39	17.78	1.12	2.05	20.95	62.64	1.42	1.64	3.26	6.32	NA ^b
CPT-03M	3M	3/23/95	134.41	14.03	21.8	58.18	32.43	32.14	122.75	292.99	7.75	30.67	18.58	57	35.8
CPT-03S	3S	3/23/95	1496.39	1526.23	2252.51	2855.12	3466.78	2498.73	8820.63	14095.76	776.78	2903.48	850.57	4530.83	181.9
CPT-09D	9D	3/25/95	44.78	4.35	0.98	4.81	5.36	14.18	5	64.29	1.38	1.45	7.26	10.09	21.8
CPT-09S	9S	3/25/95	1.09	BLQ	1.29	1.82	1.73	1.45	5	7.38	1.09	2.46	3.6	7.15	3
CPT-12D	12D	3/25/95	BLQ	BLQ	BLQ	1.21	1.33	0.99	3.53	3.53	1.15	1.33	2.75	5.23	10.9
CPT-12S	12S	3/25/95	BLQ	ND ^c	BLQ	BLQ	1.08	BLQ	1.08	1.08	ND	ND	1.27	1.27	6.1
CPT-26D	26D	3/26/95	BLQ	ND	BLQ	BLQ	0.96	ND	0.96	0.96	1.04	ND	ND	1.04	9.5
CPT-26S	26S	3/26/95	BLQ	1.67	ND	BLQ	BLQ	ND	BLQ	1.67	1.06	1.31	ND	2.37	3.4
CPT-04D	86-4D	3/25/95	BLQ	1	BLQ	1.06	1.13	1.35	3.54	4.54	1.11	ND	1.98	3.09	7.8
CPT-04S	86-4S	3/23/95	BLQ	0.97	BLQ	1.06	1.22	1.3	3.58	4.55	1.27	ND	1.84	3.11	7.5
CPT-04S	86-4S DUP	3/23/95	BLQ	ND	BLQ	BLQ	0.99	BLQ	0.99	0.99	ND	1.7	1.42	3.12	7.5
CPT-16DD	86-16DD	3/31/95	BLQ	BLQ	BLQ	BLQ	1.03	BLQ	1.03	1.03	ND	ND	ND	ND	4.6
CPT-18D	86-MW18D	3/24/95	ND	ND	ND	BLQ	BLQ	ND	BLQ	BLQ	ND	ND	ND	ND	5.8
CPT-18DD	86-MW18DD	3/31/95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	4.2
CPT-18S	86-MW18S	3/24/95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	4
MW-100	86-MW100	3/23/95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3.3
CPT-21D	86-MW21D	3/25/95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	NA
CPT-21S	86-MW21S	3/25/95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	4.9
MW-1 ^w	-	5/95	ND	ND	ND	NA	NA	NA	ND	ND	NA	NA	NA	NA	NA
MW-2 ^w	-	5/95	ND	ND	ND	NA	NA	NA	ND	ND	NA	NA	NA	NA	NA
MW-3 ^w	-	5/95	ND	ND	ND	NA	NA	NA	ND	ND	NA	NA	NA	NA	NA
MW-4 ^w	-	5/95	ND	ND	ND	NA	NA	NA	ND	ND	NA	NA	NA	NA	NA
MW-6 ^w	-	5/95	ND	ND	ND	NA	NA	NA	ND	ND	NA	NA	NA	NA	NA
MW-7 ^w	-	5/95	ND	ND	ND	NA	NA	NA	ND	ND	NA	NA	NA	NA	NA
MW-8 ^w	-	5/95	140	85	270	NA	NA	NA	2450	2945	NA	NA	NA	NA	NA
MW-9 ^w	-	5/95	37	ND	46	NA	NA	NA	ND	83	NA	NA	NA	NA	NA
MW-10 ^w	-	5/95	180	ND	360	NA	NA	NA	220	760	NA	NA	NA	NA	NA
MW-11 ^w	-	5/95	ND	ND	ND	NA	NA	NA	ND	ND	NA	NA	NA	NA	NA
MW-12 ^w	-	5/95	210	ND	700	NA	NA	NA	2310	3220	NA	NA	NA	NA	NA

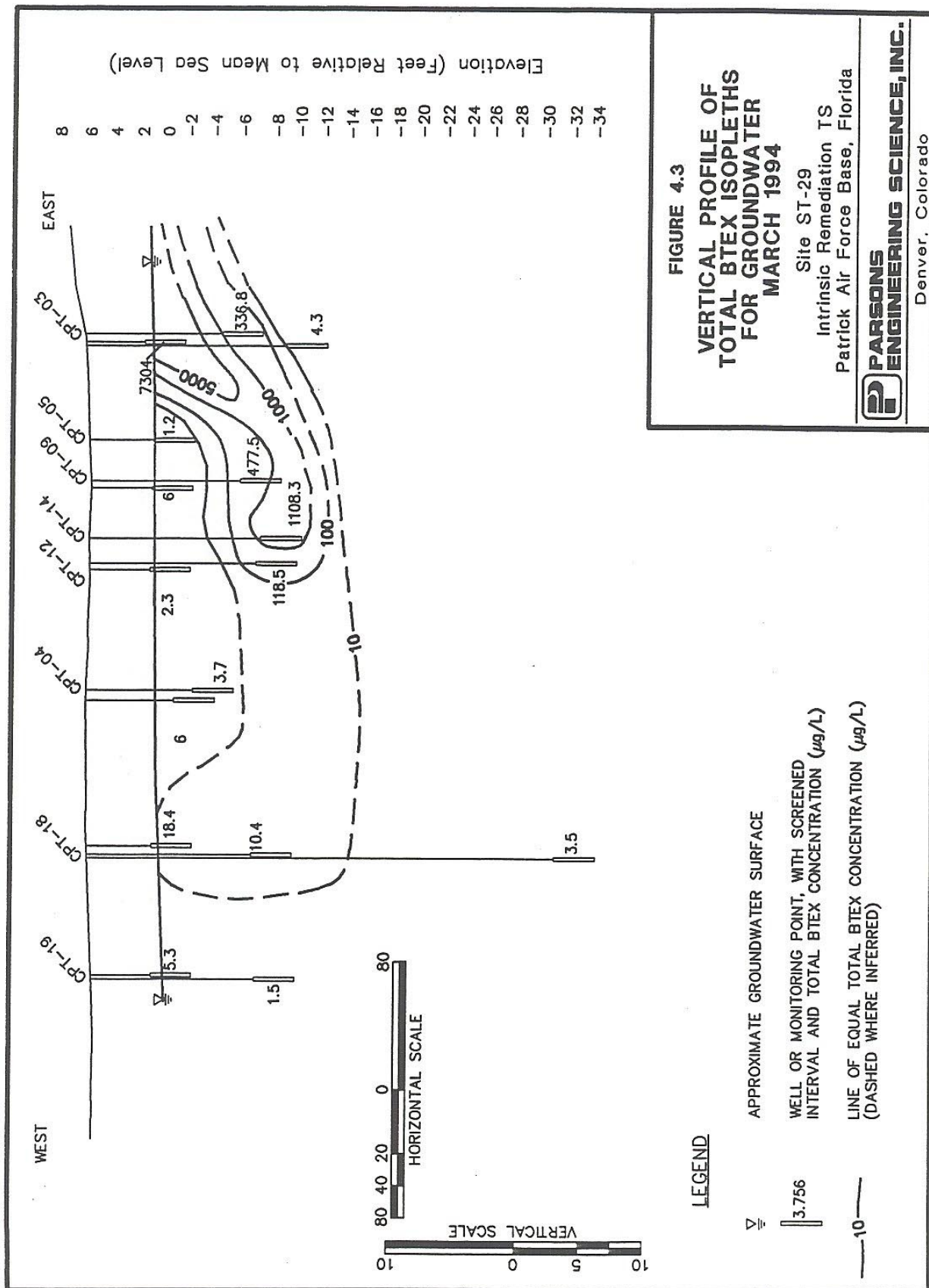
^a BLQ = Below limit of quantitation, 1.0 µg/L.

^b NA = Data not available or sample not analyzed for this parameter.

^c ND = Compound not detected at the method detection limit.

^d Sample collected and analyzed by CH2M Hill on May 10 and 11, 1995.





the plume was approximately 560 feet in length and 200 feet in width at the widest point in March 1994. As defined by the 100 $\mu\text{g/L}$ isopleth, the plume was 300 feet long by 80 feet wide (at its widest point) in March 1994. As indicated by the March 1994 vertical profile, the plume is migrating downward in the vicinity of CPT-03, CPT-05, and CPT-09. Based on March 1994 data, the plume appears to be leveling out downgradient from CPT14, although the plume geometry is not well defined beyond that point.

In March 1994, 10 monitoring points/wells at the site contained groundwater with dissolved benzene concentrations above the Florida regulatory maximum contaminant level (MCL) of 1 $\mu\text{g/L}$. Where detected in March 1994, benzene concentrations ranged from 1 to 960 $\mu\text{g/L}$, with the maximum detected benzene concentration at CPT-14D (the deep point at that nest). Toluene concentrations ranged from 1 to 737 $\mu\text{g/L}$, with the maximum detected toluene concentration at CPT-14D; most toluene concentrations were in the range of 1 to 18.9 $\mu\text{g/L}$ in March 1994. In March 1994, ethylbenzene was detected much less frequently than benzene or toluene. Where detected, total xylene concentrations ranged from 1 to 5,020 $\mu\text{g/L}$. The highest concentration was detected in CPT-03S; concentrations elsewhere were generally below 120 $\mu\text{g/L}$.

Contaminant data collected in March and May 1995, also show that dissolved BTEX contamination is migrating to the west in the direction of groundwater flow. As defined by the 5 $\mu\text{g/L}$ total BTEX isopleth, the plume was approximately 480 feet in length and 120 feet in width at the widest point during this period. Thus, the total BTEX plume contracted considerably between March 1994 and March/May 1995.

Available dissolved BTEX data indicate that the BTEX plume receded and shrank in both the longitudinal and lateral directions between March 1994 and March/May 1995 (compare Figures 4.2 and 4.4). In addition, maximum observed total BTEX concentrations, in general, decreased during the same time period. This is illustrated by Figure 4.5, which was prepared from monitoring data collected from March 1994 and March 1995. For clarity, only sampling points with total BTEX concentrations greater than 10 $\mu\text{g/L}$ are shown on Figure 4.5. Also for purposes of clarity, Figure 4.5 has been split into two plots. Figure 4.5A shows data from sampling points where a decrease in contaminant concentrations was observed between March 1994 and March/May 1995. Figure 4.5B shows data from sampling points where an increase in contaminant

FIGURE 4.5A

PLOT OF TOTAL BTEX VERSUS TIME FOR SAMPLING LOCATIONS
WITH DECREASING BTEX CONCENTRATIONS
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

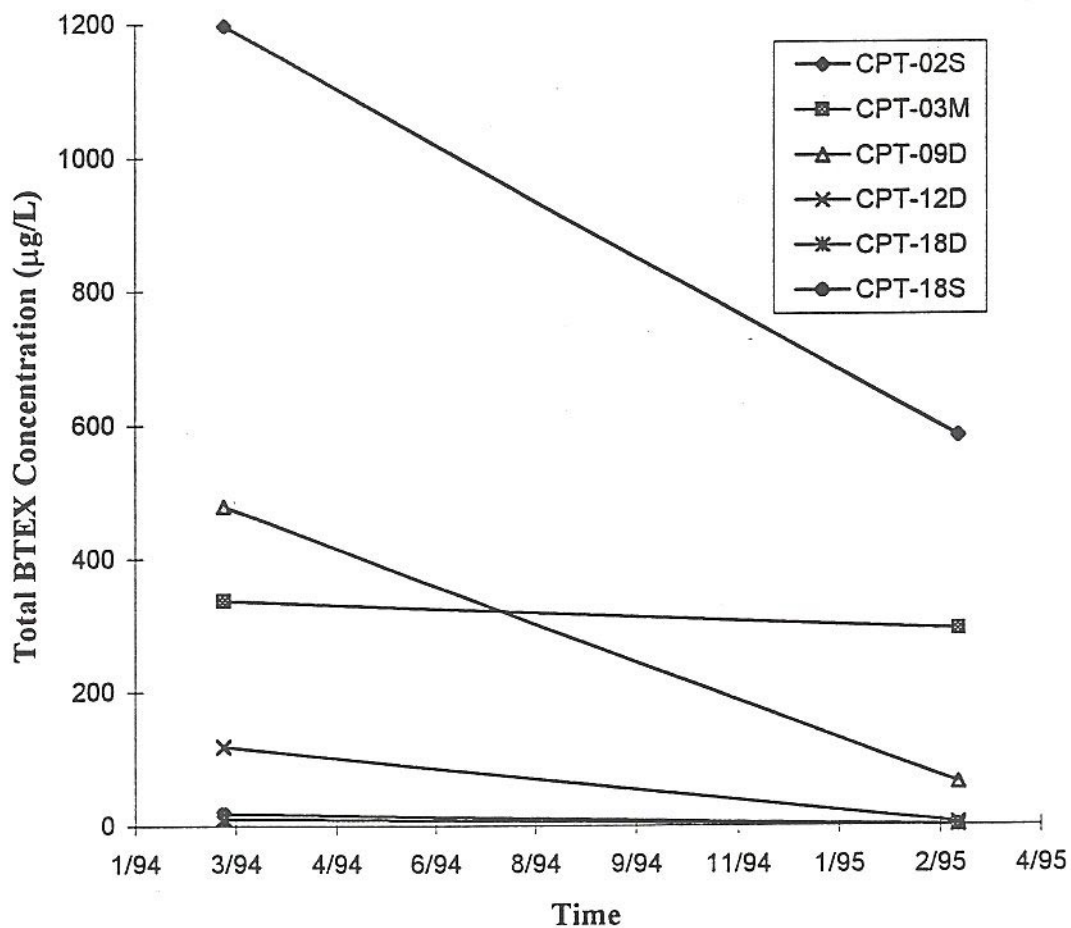
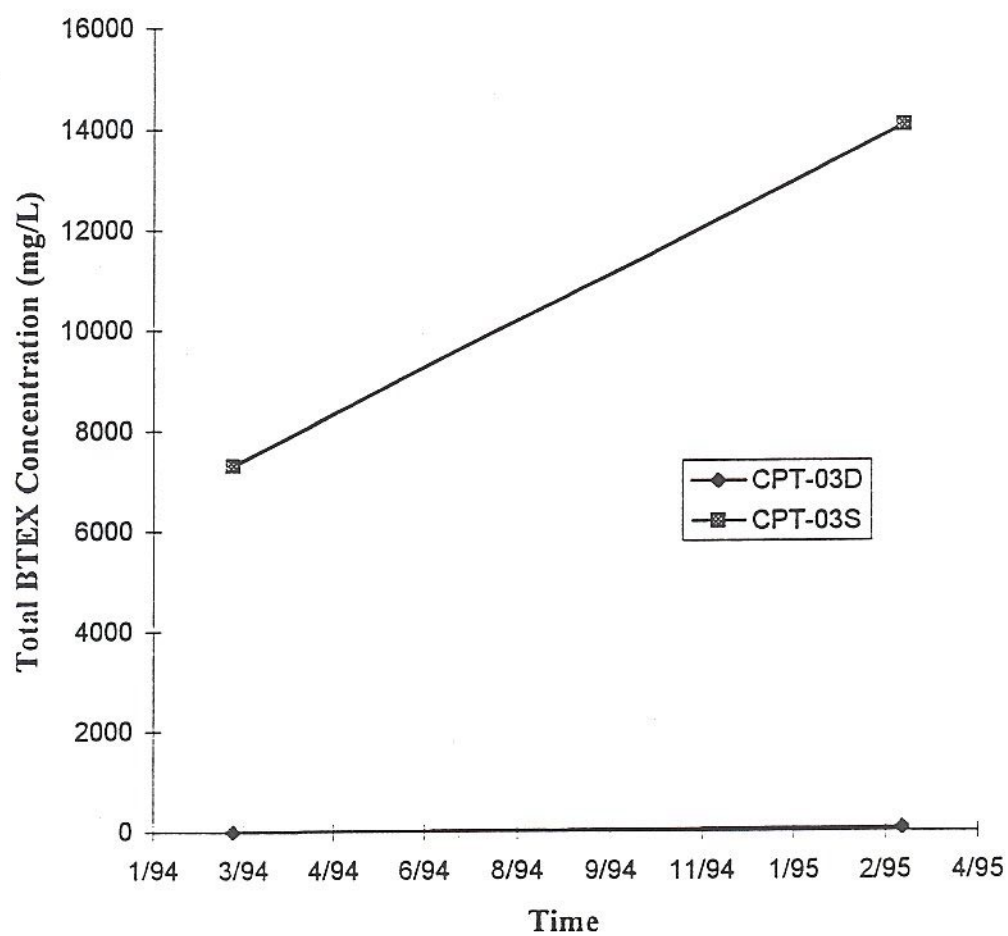


FIGURE 4.5B

PLOT OF TOTAL BTEX VERSUS TIME FOR SAMPLING LOCATIONS
WITH INCREASING BTEX CONCENTRATIONS
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA



concentrations was observed between March 1994 and March/May 1995. From these figures it appears that, with the exception of data collected at sampling points CPT-03S and CPT-03D, total BTEX concentrations at the site are decreasing. The combination of decreasing contaminant concentrations and the smaller plume area imply that dissolved BTEX is being removed from the system, because the apparent mass loss cannot be attributed to plume spreading (i.e., dilution due to dispersion).

On the basis of the advective groundwater transport velocity calculated in Section 3.3.2.4, the BTEX plume should have migrated between 110 and 220 feet downgradient (excluding biodegradation and sorption) between March 1994 and March/May 1995. Given that the plume receded during this period, it appears that biodegradation has been effective in preventing downgradient migration of the dissolved BTEX plume. In conjunction with the evidence of decreasing contaminant concentrations, this is a further indication that contaminant mass is being lost, most likely due to biodegradation and other natural attenuation mechanisms.

4.3.3 Groundwater Geochemistry

Microorganisms obtain energy for cell production and maintenance by catalyzing the transfer of electrons from electron donors to electron acceptors. This results in the oxidation of the electron donor and the reduction of the electron acceptor. Electron donors at Site ST-29 are natural organic carbon and fuel hydrocarbon compounds. Fuel hydrocarbons are completely degraded (or detoxified) if they are utilized as the primary electron donor for microbial metabolism (Bouwer, 1992). Electron acceptors are elements or compounds that occur in relatively oxidized states and include oxygen, nitrate, ferrous iron, sulfate, and carbon dioxide. Microorganisms preferentially utilize electron acceptors while metabolizing fuel hydrocarbon (Bouwer, 1992). DO is utilized first as the prime electron acceptor. After the DO is consumed, anaerobic microorganisms use electron acceptors in the following order of preference: nitrate, ferric iron, sulfate, and finally carbon dioxide.

Depending on the type of electron acceptors present (e.g., nitrate, ferric iron, sulfate, or carbon dioxide), pH conditions, and redox potential, anaerobic biodegradation can occur by denitrification, ferric iron reduction, sulfate reduction, or methanogenesis. Other, less common anaerobic degradation mechanisms such as manganese reduction may dominate if the physical and

chemical conditions in the subsurface favor use of these electron acceptors. Anaerobic destruction of the BTEX compounds is associated with the accumulation of fatty acids, production of methane, solubilization of iron, and reduction of nitrate and sulfate (Cozarelli *et al.*, 1990; Wilson *et al.*, 1990). Environmental conditions and microbial competition will ultimately determine which processes will dominate. Vrobesky and Chapelle (1994) show that the dominant terminal electron accepting process can vary both temporally and spatially in an aquifer with fuel hydrocarbon contamination.

Site ST-29 data for electron acceptors such as nitrate and sulfate do not indicate intrinsic remediation of hydrocarbons in the shallow aquifer by denitrification or sulfate reduction. However, ferrous iron (Fe^{2+}) data suggest a minor amount of anaerobic degradation via ferric iron reduction. Methane data suggest that methanogenesis is the most significant anaerobic process. Geochemical parameters for Site ST-29 groundwater are discussed in the following sections.

4.3.3.1 Dissolved Oxygen

DO concentrations were measured at groundwater monitoring points and at existing monitoring wells in March 1994. Table 4.5 summarizes DO concentrations measured in March 1995. In addition, DO concentrations were measured at select groundwater monitoring points in March 1995. Table 4.6 summarizes DO concentrations measured in March 1995. Figure 4.6 is an isopleth map showing the distribution of DO concentrations in groundwater in March 1994, and Figure 4.7 is a vertical section through the DO plume during this same period. Comparison of Figures 4.2 and 4.6 and Figures 4.3 and 4.7 shows graphically that areas with elevated total BTEX concentrations correlate with areas with depleted DO concentrations. This is a strong indication that aerobic biodegradation of the BTEX compounds is occurring at the site. Based on the background DO concentrations measured at the site in March 1994 (up to 3.7 mg/L), it is likely that DO is an important electron acceptor at Site ST-29.

The following equations describe the overall stoichiometry of aromatic hydrocarbon mineralization caused by microbial biodegradation. In the absence of microbial cell production, the oxidation (mineralization) of benzene to carbon dioxide and water is given by:

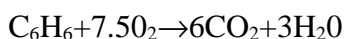


TABLE 4.5

**GROUNDWATER GEOCHEMICAL DATA, MARCH 1994
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA**

Sample Location	Sample Number	Water Temp. (°C)	pH	Conductivity (µmhos/cm)	Dissolved Oxygen (mg/L)	Redox Potential (mV)	Total Alkalinity (mg/L)	Hydrogen Sulfide (mg/L)	Ferrous Iron (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	NO ₂ +NO ₃ Nitrogen (mg/L)	TOC ^w (mg/L)	Methane (mg/L)
CPT-01	CPT-86-001	24.7	NA ^w	NA	0.4	NA	NA	NA	NA	44.4	4.37	0.13	14	4.99
CPT-02D	CPT-86-002D	24.7	7.1	771	0.6	-190	330	0.4	0.4	45.7	ND2 ^e	0.13	6.8	5.953
CPT-02S	CPT-86-002S	24.7	6.7	1061	0.2	-156	498	0.2	1.6	42.6	ND2	0.12	16.9	14.953
CPT-03D	CPT-86-003D	NA	7.3	721	NA	-255	315	1	0.4	41.6	ND2	0.12	5.4	1.63
CPT-03M	CPT-86-003M	26.4	7.1	898	0.2	-50	398	0	0.3	40.7	2.52	0.11	10.9	3.164
CPT-03S	CPT-86-003S	26.4	6.7	1733	0.1	-208	520	0.1	1.2	132	118	14.8	63.1	14.021
CPT-04D	CPT-86-004D	26.1	7.2	457	0.2	-266	212	0.2	0.6	12.4	1.47	0.09	5.6	3.756
CPT-04S	CPT-86-004S	26.9	6.9	469	0.3	-286	215	0.5	0.6	12.5	ND2	0.19	6.6	7.661
CPT-05S	CPT-86-005S	26.4	7.3	488	1.1	-160	215	0.1	0.1	23.6	6.86	0.17	12	4.858
CPT-06S	CPT-86-006S	25.1	7.6	437	0.2	-278	148	1.5	0.3	47.8	7.03	0.13	3.8	6.595
CPT-07S	CPT-86-007S	25.3	7.2	577	0.2	-250	254	1.2	1	30.2	2.52	0.12	3.4	6.339
CPT-08S	CPT-86-008S	25	7.1	974	0.2	-60	420	0	1.9	44.7	8.51	0.1	10.1	1.742
CPT-09D	CPT-86-009D	27.8	7.1	938	0.3	-200	422	0.6	0.2	34.7	15.3	0.11	12	4.236
CPT-09S	CPT-86-009S	27.3	7.3	530	0.2	-24	340	0	0.2	14.3	6.64	0.1	10.2	3.797
CPT-10S	CPT-86-010S	26	7.3	460	0.1	-60	192	0	0.2	26.6	9.5	0.13	21.3	3.493
CPT-11S	CPT-86-011S	25.9	7.2	508	0.1	-35	210	0	0.4	12.7	15.9	0.15	NA	4.244
CPT-12D	CPT-86-012D	27.1	7.2	715	0.4	10	329	0.1	0.1	28.1	3.86	0.12	8.1	0.983
CPT-12S	CPT-86-012S	27.3	7	564	0.9	30	266	0	0.1	15.2	8.38	0.1	10.5	5.372
CPT-13S	CPT-86-013S	25.7	7.3	801	0.1	-230	362	0.6	0.3	35.5	6.94	0.12	7.2	2.043
CPT-14D	CPT-86-014D	25.5	7	906	0.3	-240	460	0.6	0.3	34.6	3.68	0.11	12.8	8.793
CPT-16DD	CPT-86-016DD	26.7	NA	NA	2.7	NA	NA	0.3	NA	NA	NA	NA	NA	NA
CPT-16S	CPT-86-016S	25.5	7	776	0.1	-190	231	0.1	0.4	37.9	8.23	0.13	9.4	0.781
CPT-18D	CPT-86-018D	26.1	7.1	620	0.3	-60	294	0.2	0.3	15	1.85	0.11	5.6	4.56
CPT-18DD	CPT-86-018DD	27.3	NA	NA	2.3	NA	NA	0	NA	NA	NA	NA	NA	NA
CPT-18S	CPT-86-018S	26.6	6.9	834	2	25	286	0	0.5	36.6	86	0.12	7.8	NA
CPT-19D	CPT-86-019D	26.6	7.1	744	0.2	-50	328	0.2	0.2	33.7	1.51	0.1	7.3	2.136
CPT-19S	CPT-86-019S	NA	7	800	NA	41	335	0	0.1	37.4	8.85	0.11	10.3	0.924
CPT-20D	CPT-86-020D	25.7	7.1	842	0.3	-44	380	0.1	0.2	52	ND2	0.07	8.6	1.114
CPT-20S	CPT-86-020S	25	7	368	1.5	23	148	0	0.3	9.83	25.5	0.1	3.6	1.278
CPT-21D	CPT-86-021D	26.4	7.2	716	0.2	-20	304	0.1	0.2	29.8	13.3	0.14	6.1	0.46
CPT-21S	CPT-86-021S	26	7.1	610	3.2	20	245	0	0.2	26.6	25.5	0.29	7.6	2.414
CPT-22D	CPT-86-022D	25.4	6.9	936	0.1	-287	415	5	0.2	NA	NA	0.12	11.4	0.866

TABLE 4.5 (CONCLUDED)

GROUNDWATER GEOCHEMICAL DATA, MARCH 1994
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

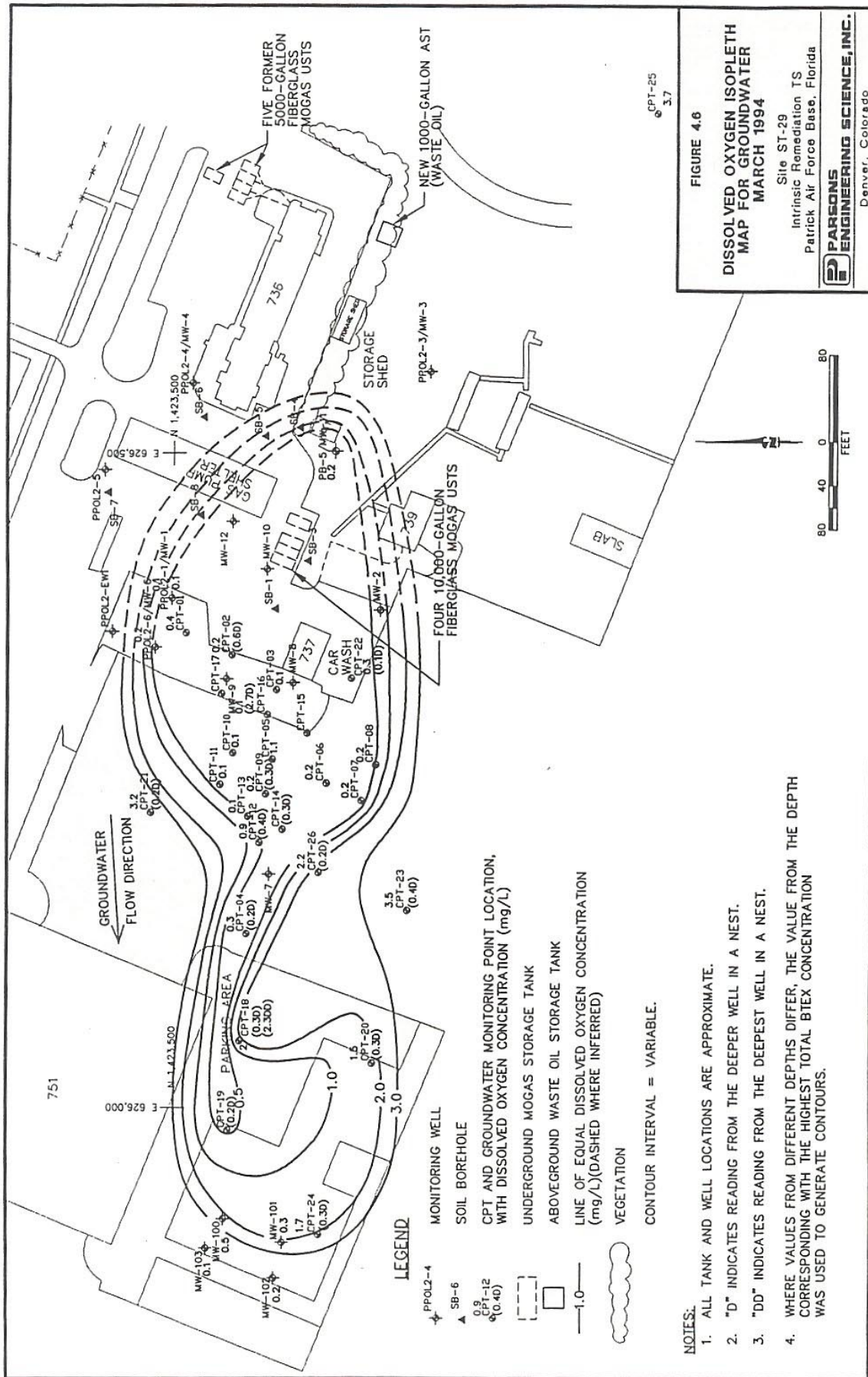
Sample Location	Sample Number	Water Temp. (°C)	pH	Conductivity (µmhos/cm)	Dissolved Oxygen (mg/L)	Redox Potential (mV)	Total Alkalinity (mg/L)	Hydrogen Sulfide (mg/L)	Ferrous Iron (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	NO ₃ +NO ₂ Nitrogen (mg/L)	TOC ^a (mg/L)	Methane (mg/L)
CPT-22S	CPT-86-022S	25.5	6.8	1271	0.3	-153	450	0	1.2	66.6	128	0.07	10	3.218
CPT-23D	CPT-86-023D	26.7	7.1	779	0.4	-167	332	0.2	0.2	36.1	1.49	0.1	8.2	2.282
CPT-23S	CPT-86-023S	26.5	6.9	757	3.5	54	346	0	0.2	23.4	ND2	0.12	6.4	1.992
CPT-24D	CPT-86-024D	26	7.5	376	0.3	-60	192	0.1	0.1	5.46	3.61	0.1	2.8	0.686
CPT-24S	CPT-86-024S	25.7	7	338	1.7	30	190	0	0.1	6.63	ND2	0.12	5.6	2.204
CPT-25D	CPT-86-025D	NA	7.1	892	NA	62	371	0	ND1 ^d	5.17	6.16	0.12	15.7	1.556
CPT-25S	CPT-86-025S	25	7.3	664	3.7	53	157	0	ND1	28	51.9	0.12	15.7	0.147
CPT-26D	CPT-86-026D	26.2	7	751	0.2	-293	311	3	0.4	44.9	19.8	0.11	8.3	2.961
CPT-26S	CPT-86-026S	26	7.6	558	2.2	-20	264	0	0.3	15.1	1.22	0.12	5	3.569
MW-100	CPT-86-100	25.9	7.2	607	0.5	-241	331	0.2	0.1	24.9	16.3	0.12	18.6	2.821
MW-101	CPT-86-101	26.5	7.2	533	0.3	-247	287	0.8	0.1	21.6	5.75	0.13	9	2.308
MW-102	CPT-86-102	25.8	7.2	523	0.2	-281	250	0.5	0.1	17.9	3.51	0.12	7.6	3.256
MW-103	CPT-86-103	25.4	7.4	445	0.1	-271	209	1	0.1	12.5	4.69	0.11	2.6	5.291
PB5	CPT-86-PB5	24.9	7.1	743	0.2	-140	291	NA	ND1	51.4	4.45	0.1	NA	4.414
PPOL-2-1	CPT-86-PPOL-2-1	26.3	7.1	747	0.1	-220	305	0.7	0.6	44	3.2	ND1	NA	5.33
PPOL-2-6	CPT-86-PPOL-2-6	27.2	7	30100	0.2	-230	334	0.8	NA	10200	1150	ND1	NA	0.034

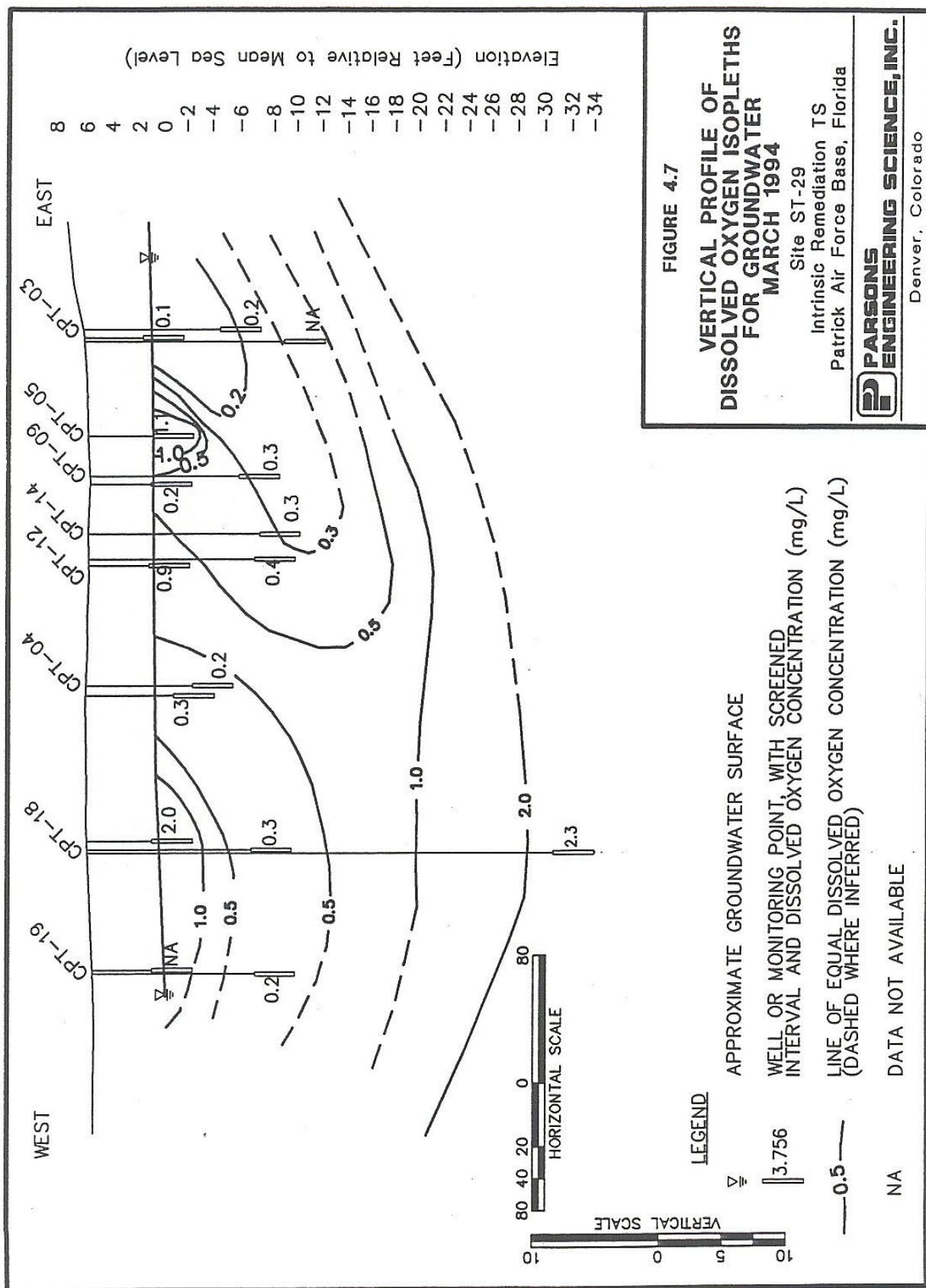
^a TOC = Total organic carbon.^b NA = Not available.^c ND2 = <0.5 mg/L.^d ND1 = <0.05 m/L.

TABLE 4.6
GROUNDWATER GEOCHEMICAL DATA, MARCH 1995
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Sample Location	Sample Number	Sample Date	pH	Conductivity (µS/cm)	Redox (mv)	Alkalinity (mg/L CaCO ₃)	Chloride (mg/L)	Dissolved Oxygen (mg/L)	Nitrate + Nitrite (mg/L)	Ammonia (mg/L)	Ferrous Iron (mg/L)	Manganese (mg/L)	Sulfate (mg/L)	Hydrogen Sulfide (mg/L)	Carbon Dioxide (mg/L)	Methane (mg/L)
CPT-02S	2S	3/23/95	6.54	998	-231	404	62.7	0.1	0.06	3.83	1.1	<0.1	1.13	NA ^a	420	12.846
CPT-02S	2S DUP	3/23/95	6.53	995	-225	407	67.7	0.1	0.07	3.79	1.1	<0.1	1.08	NA	416	14.15
CPT-03D	3D	3/23/95	7.02	787	-348	341	46.5	0.1	0.08	1.18	<0.05	<0.1	15.7	5	144	2.57
CPT-03D	3D DUP	3/23/95	7.04	786	-347	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
CPT-03M	3M	3/23/95	6.77	1019	-343	447	42.6	<0.1	0.06	6.13	<0.05	<0.1	19.6	NA	338	12.437
CPT-03S	3S	3/23/95	6.72	2010	-357	920	129	<0.1	<0.05	18.2	0.1	<0.1	14	NA	780	15.534
CPT-09D	9D	3/25/95	6.78	995	-293	469	51.1	0.1	0.06	3.85	<0.05	<0.1	2.23	5	284	9.839
CPT-09S	9S	3/25/95	7.38	391	-279	180	9.46	0.1	0.07	1.71	0.1	<0.1	1.52	1	80	5.822
CPT-12D	12D	3/25/95	6.93	946	-340	359	56.9	<0.1	0.05	2.37	<0.05	<0.1	49.7	5	202	0.882
CPT-12S	12S	3/25/95	7.05	498	-306	220	14.4	<0.1	0.07	4.04	0.3	<0.1	0.98	1	142	12.339
CPT-26D	26D	3/26/95	6.88	837	-342	357	51.2	0.1	0.06	2.61	<0.05	<0.1	3.31	5	192	3.756
CPT-26S	26S	3/26/95	6.87	440	-269	202	13.2	0.1	0.07	1.01	0.3	<0.1	0.94	0.7	154	9.009
CPT-04D	86-41D	3/25/95	7.04	540	-325	259	18.4	<0.1	0.07	2.53	0.1	<0.1	2.98	5	90	5.095
CPT-04S	86-4S	3/23/95	6.85	543	-289	263	15.8	0.1	0.07	3.6	0.1	<0.1	1.17	1	138	11.63
CPT-04S	86-4S DUP	3/23/95	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	10.594
CPT-16DD	86-16DD	3/31/95	7.13	26900	-288	307	9830	0.1	<0.05	16.9	<0.05	<0.1	1200	NA	238	0.074
CPT-18D	86-MIW18D	3/24/95	6.87	652	-316	289	29.6	0.1	0.07	1.52	0.1	<0.1	1.08	2	98	6.116
CPT-18DD	86-MIW18DD	3/31/95	7.19	26500	-171	335	9080	0.2	<0.05	16.2	0.1	<0.1	967	<0.1	276	0.068
CPT-18S	86-MIW18S	3/24/95	6.85	675	-287	276	18.3	0.1	0.07	0.35	0.2	<0.1	59.6	0.7	110	3.379
MW-100	86-MIW100	3/25/95	7.32	429	-253	205	15.2	<0.1	0.07	0.23	0.3	<0.1	10	0.3	132	NA
CPT-21D	86-MIW21D	3/25/95	7.18	674	-307	287	28.2	<0.1	0.07	0.47	0.1	NA	38.8	5	96	0.749
CPT-21S	86-MIW21S	3/25/95	6.92	381	-239	177	12.3	0.1	0.08	2.94	0.6	NA	0.52	0.7	190	9.857

a/ NA = Data not available.





Therefore, 7.5 moles of oxygen are required to metabolize 1 mole of benzene. On a mass basis, the ratio of oxygen to benzene is given by:

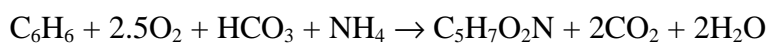
Molecular weights: Benzene	$6(12) + 6(1) = 78$ grams (gm)/mole
Oxygen	$7.5(32) = 240$ gm/mole

$$\text{Mass Ratio of Oxygen to Benzene} = 240/78 = 3.08:1$$

Therefore, in the absence of microbial cell production, 3.08 mg of oxygen are required to completely metabolize 1 mg of benzene.

Similar calculations can be completed for toluene (3.13 mg oxygen to 1 mg toluene), ethylbenzene (3.17 mg oxygen to 1 mg ethylbenzene), and the xylenes (3.17 mg oxygen to 1 mg xylene). The average mass ratio of oxygen to total BTEX is thus 3.14:1. This means that approximately 0.32 mg of BTEX is mineralized for every 1.0 mg of DO consumed. With a background DO concentration of approximately 3.7 mg/L, the shallow groundwater at this site has the capacity to assimilate 1.2 mg/L (1,200 $\mu\text{g/L}$) of total BTEX. This is a conservative estimate of the assimilative capacity of DO because microbial cell mass production was not taken into account by the stoichiometry shown above.

When cell mass production is accounted for, the mineralization of benzene to carbon dioxide and water is given by:



From this it can be seen that only 2.5 moles of DO are required to mineralize 1 mole of benzene when cell mass production is taken into account. On a mass basis, the ratio of DO to benzene is given by:

Molecular weights: Benzene	$6(12) + 6(1) = 78$ gm/mole
Oxygen	$2.5(32) = 80$ gm/mole

$$\text{Mass Ratio of Oxygen to Benzene} = 80/78 = 1.03:1$$

Based on these stoichiometric relationships, 1.03 mg of oxygen are required to mineralize 1 mg of benzene. Similar calculations can be made for toluene, ethylbenzene, and the xylenes. Based on these calculations, approximately 0.97 mg of BTEX is mineralized to carbon dioxide and water for every 1.0 mg of DO consumed. With a

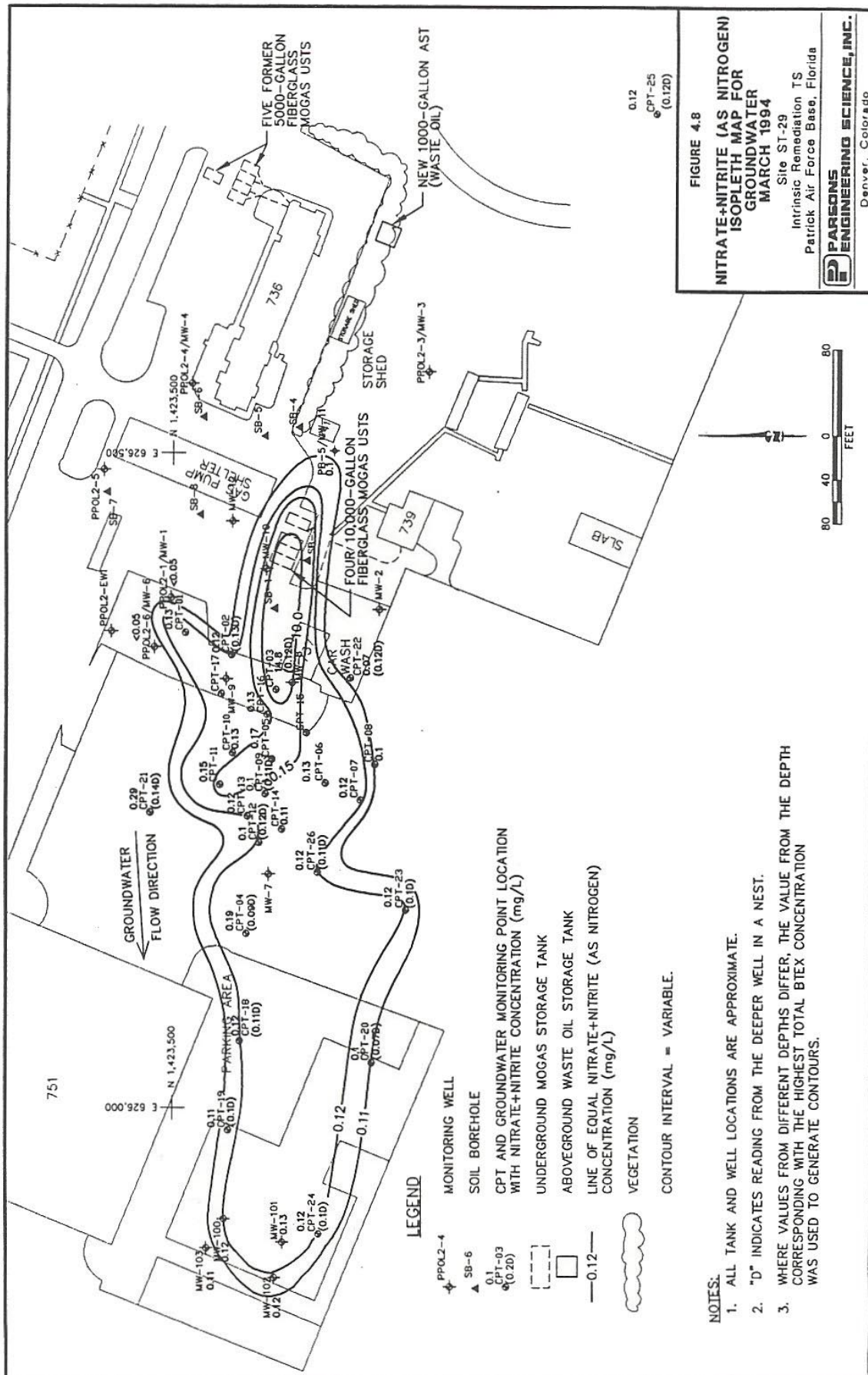
background DO concentration of approximately 3.7 mg/L, the shallow groundwater at this site has the capacity to assimilate 3.6 mg/L (3,600 µg/L) of total BTEX if microbial cell mass production is taken into account.

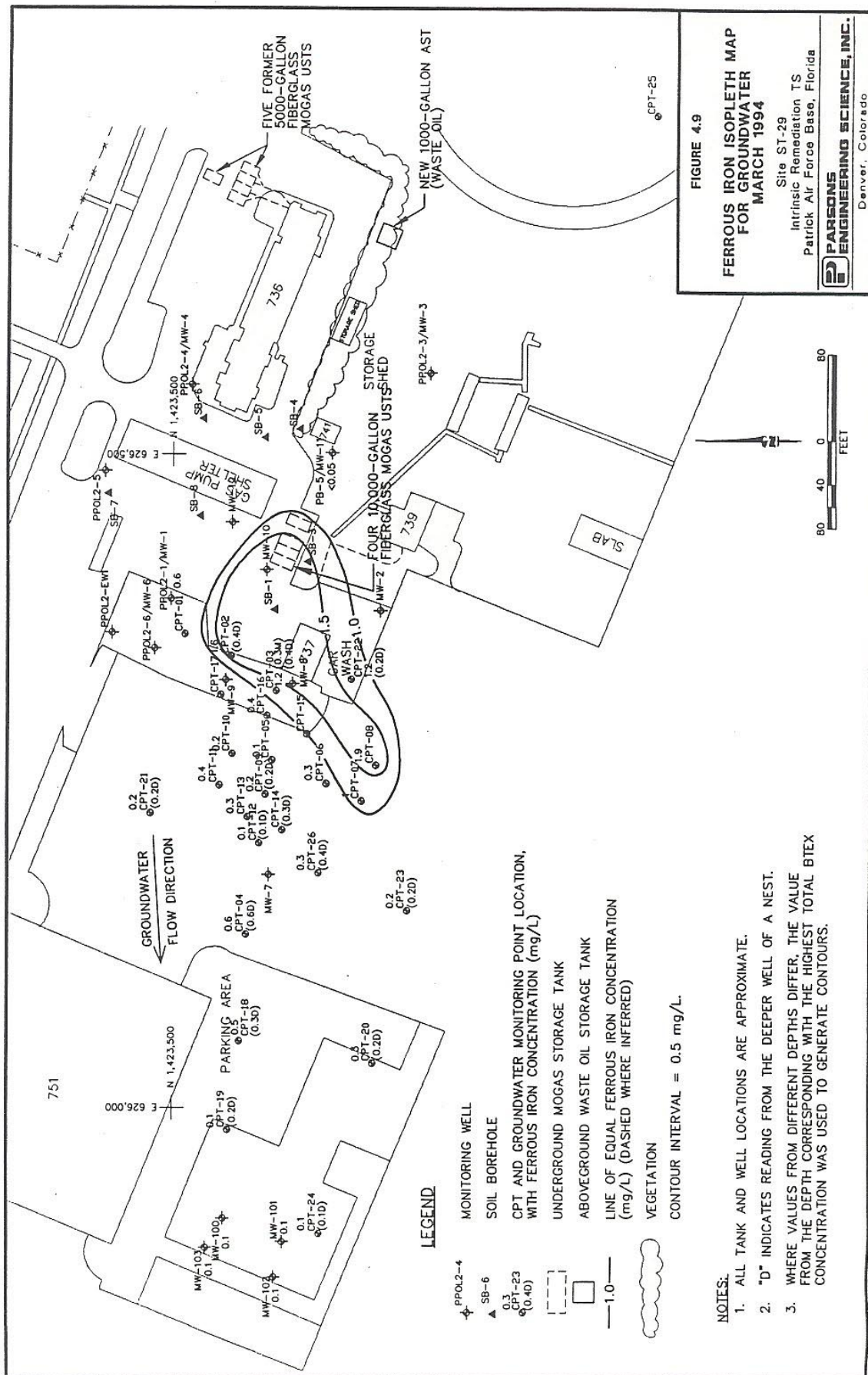
4.3.3.2 Nitrate/Nitrite

Concentrations of nitrate + nitrite [as nitrogen (N)] were measured at groundwater monitoring points and at existing monitoring wells in March 1994. Table 4.5 summarizes measured nitrate and nitrite concentrations in March 1994. Concentrations of nitrate + nitrite (as N) were measured at select groundwater monitoring points in March 1995. Table 4.6 summarizes measured nitrate and nitrite concentrations in March 1995. With the exception of one anomalously high nitrate concentration in March 1994 (14.8 mg/L at CPT-03), nitrate concentrations are extremely low at this site, ranging from <0.05 mg/L to only 0.29 mg/L. Figure 4.8 is an isopleth map showing the distribution of nitrate + nitrite (as N) in groundwater. Comparison of this figure with Figure 4.2 shows graphically that areas with elevated total BTEX concentrations have slightly elevated nitrate + nitrite concentrations. The extremely low background nitrate concentrations observed at this site suggest that anaerobic biodegradation of the BTEX compounds by nitrate reduction is not a significant removal mechanism.

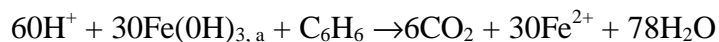
4.3.3.3 Ferrous Iron

Ferrous iron concentrations were measured at groundwater monitoring points and at existing monitoring wells in March 1994. Table 4.5 summarizes ferrous iron concentrations in March 1994. Ferrous iron concentrations were measured at select groundwater monitoring points in March 1995. Table 4.6 summarizes ferrous iron concentrations in March 1995. Figure 4.9 is an isopleth map showing the distribution of ferrous iron in groundwater in March 1994. Comparison of Figures 4.9 and 4.2 shows graphically that the area nearest the car wash with elevated total BTEX concentrations has slightly elevated ferrous iron concentrations. This suggests that ferric iron is potentially being reduced to ferrous iron during biodegradation of BTEX compounds. The highest measured ferrous iron concentration (March 1994), 1.9 mg/L, was observed at CPT-08. A ferrous iron concentration of 1.2 mg/L (March 1994) was observed at CPT-03 (shallow), which is also the location of the highest detected BTEX concentration. Background concentrations of ferrous iron are generally at or below 0.1 mg/L, as measured at wells with little or no known BTEX contamination.





The following equations describe the overall stoichiometry of benzene oxidation by iron reduction caused by anaerobic microbial biodegradation. In the absence of microbial cell production, the mineralization of benzene is given by:



Therefore, 30 moles of ferric iron are required to metabolize 1 mole of benzene. On a mass basis, the ratio of ferric iron to benzene is given by:

$$\begin{aligned} \text{Molecular weights: Benzene } 6(12) + 6(1) &= 78 \text{ gm/mole} \\ \text{Ferric Iron } 30(106.85) &= 3205.41 \text{ gm/mole} \end{aligned}$$

$$\text{Mass ratio of ferric iron to benzene} = 3205.41/78 = 41.1:1$$

Therefore, in the absence of microbial cell production, 41.1 mg of ferric iron are required to completely metabolize 1 mg of benzene. Alternatively, the mass ratio of ferrous iron produced during respiration to benzene degraded can be calculated and is given by:

$$\begin{aligned} \text{Molecular weights: Benzene } 6(12) + 6(1) &= 78 \text{ gm/mole} \\ \text{Ferrous Iron } 30(55.85) &= 1675.5 \text{ gm/mole} \end{aligned}$$

$$\text{Mass ratio of ferrous iron to benzene} = 1675.5/78 = 21.5:1$$

Therefore, 21.5 mg of ferrous iron are produced during mineralization of 1 mg of benzene.

Similar calculations can be completed for toluene (21.86 mg of Fe^{2+} produced during mineralization of 1 mg of toluene), ethylbenzene (22 mg of Fe^{2+} produced during mineralization of 1 mg of ethylbenzene), and the xylenes (22 mg of Fe^{2+} produced during mineralization of 1 mg of xylene). The average mass ratio of Fe^{2+} produced during total BTEX mineralization is thus 21.8:1. This means that approximately 1 mg of BTEX is mineralized for every 21.8 mg of Fe^{2+} produced. The highest measured Fe^{2+} concentration was 1.9 mg/L. This suggests that the shallow groundwater at this site has the capacity to assimilate 0.09 mg/L (90 $\mu\text{g/L}$) of total BTEX during iron reduction. This is a conservative estimate of the assimilative capacity of iron because microbial cell mass production has not been taken into account by the stoichiometry shown above (see Section 4.3.3.1). In addition, this calculation is based on observed ferrous iron concentrations and not on the amount of ferric hydroxide available in the aquifer. Therefore, iron assimilative capacity could be much higher.

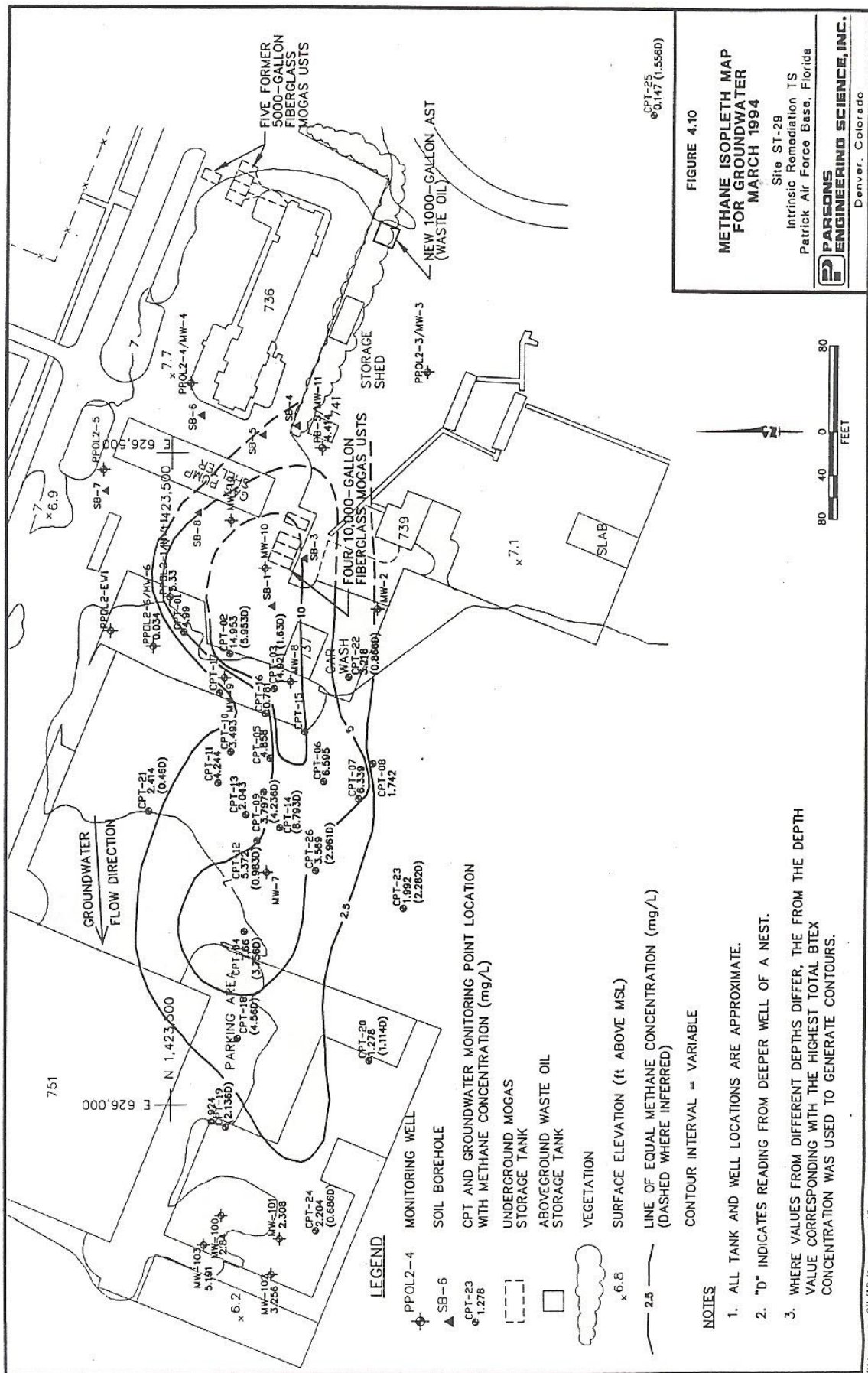
4.3.3.4 Sulfate

Sulfate concentrations were measured at groundwater monitoring points and at existing monitoring wells in March 1994. Table 4.5 summarizes measured sulfate concentrations in March 1994. Sulfate concentrations were measured at select groundwater monitoring points in March 1995. Table 4.6 summarizes measured sulfate concentrations in March 1995. No clear sulfate concentration trends are apparent at the site, and sulfate concentrations do not show a direct inverse relationship with BTEX concentrations (i.e., depleted sulfate concentrations are not present in all areas with elevated BTEX concentrations). In fact, sulfate concentrations are slightly to significantly elevated in areas associated with elevated GTEX concentrations (e.g., at CPT-03S and CPT-09D, March 1994). It appears that sulfate is not being utilized as an electron acceptor.

4.3.3.5 Methane in Groundwater

Methane concentrations were measured at groundwater monitoring points and at existing monitoring wells in March 1994. Table 4.5 summarizes methane concentrations in March 1994. Methane concentrations were measured at select groundwater monitoring points in March 1995. Table 4.6 summarizes methane concentrations in March 1995. Figure 4.10 is an isopleth map showing the distribution of methane in groundwater in March 1994. Figure 4.11 is a vertical profile of methane concentrations in March 1994. Comparison of Figures 4.2 and 4.10 and Figures 4.3 and 4.11 shows graphically that areas with elevated total BTEX concentrations correlate with elevated methane concentrations. This is a strong indication that anaerobic biodegradation of the BTEX compounds by methanogenesis is occurring at the site.

Background concentrations of methane at wells and monitoring points located outside or below areas with known BTEX contamination appear to be below 1.0 mg/L. Samples collected from monitoring wells or points located near the contaminant source area contain the highest methane concentrations. In these locations, methane concentrations range from about 1.63 to 14.59 mg/L (March 1994). The highest methane concentration observed at the site in March 1994 was in CPT-02S. The observed distribution of methane in groundwater suggests that methanogenesis may be contributing to BTEX removal in the area of highest BTEX concentrations and as far downgradient as CPT-04. This is consistent with other electron acceptor and redox potential data for this site.



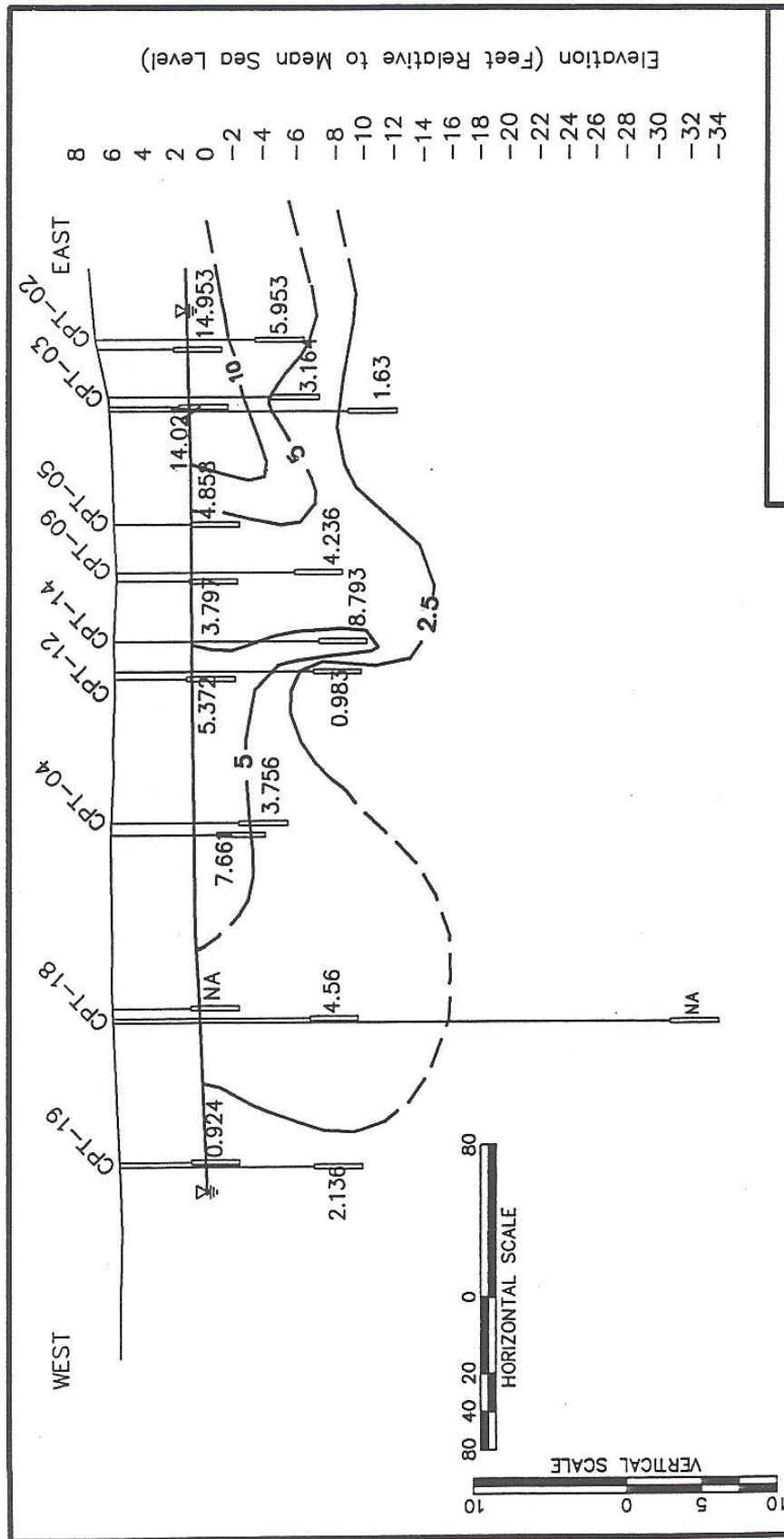


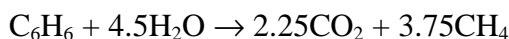
FIGURE 4.11

VERTICAL PROFILE OF
METHANE ISOPLETHS
FOR GROUNDWATER
MARCH 1994

Site St-29
Intrinsic Remediation TS
Patrick Air Force Base, Florida

PARSONS
ENGINEERING SCIENCE, INC.
Denver, Colorado

The following equations describe the overall stoichiometry of benzene oxidation by methanogenesis. In the absence of microbial cell production, the mineralization of benzene is given by:



The mass ratio of methane produced during respiration to benzene degraded can be calculated and is given by:

Molecular weights: Benzene $6(12) + 6(1) = 78$ gm/mole

Methane $3.75(16) = 60$ gm/mole

$$\text{Mass ratio of methane to benzene} = 60/78 = 0.77:1$$

Therefore, 0.77 mg of methane is produced during mineralization of 1 mg of benzene.

Similar calculations can be completed for toluene (0.78 mg of methane produced during mineralization of 1 mg of toluene), ethylbenzene (0.79 mg of methane produced during mineralization of 1 mg of ethylbenzene), and the xylenes (0.79 mg of methane produced during mineralization of 1 mg of xylene). The average mass ratio of methane produced during total BTEX mineralization is thus 0.78:1. This means that approximately 1 mg of BTEX is mineralized for every 0.78 mg of methane produced. The highest measured methane concentration in March 1994 was 14.59 mg/L. With background concentrations as high as 1.0 mg/L, the shallow groundwater at this site has the capacity to assimilate up to 17.4 mg/L (17,400 µg/L) of total BTEX during methanogenesis. Again, this is a conservative estimate of the assimilative capacity of methanogenesis because microbial cell mass production is not taken into account by the stoichiometry shown above (see Section 4.3.3.1). In addition, these calculations are based on observed methane concentrations and not on the amount of carbon dioxide available in the aquifer. Therefore, methanogenic assimilative capacity could be much higher.

4.3.3.6 Reduction/Oxidation Potential

Redox potentials were measured at groundwater monitoring points and at existing monitoring wells in March 1994. Redox potential is a measure of the relative tendency of a solution to accept or transfer electrons. The redox potential of a groundwater system depends on which electron acceptor is being reduced by microbes during BTEX oxidation. The redox potential at Site ST-29 ranges from 54 millivolts (mV) to -293 mV. Table 4.5

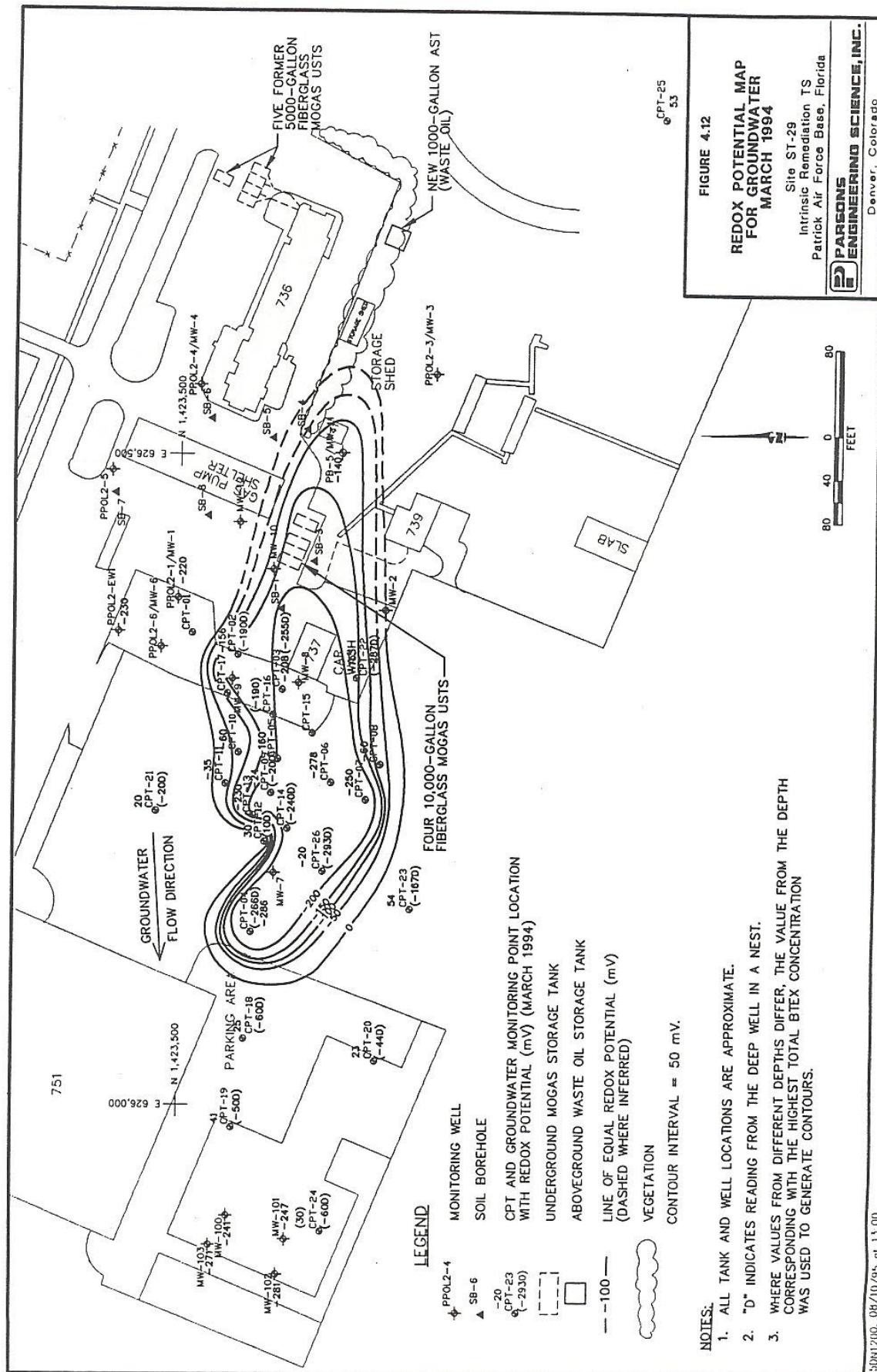
summarizes available redox potential data for March 1994. Redox potentials were measured at select groundwater monitoring points in March 1995. Table 4.6 summarizes available redox potential data for March 1995. Figure 4.12 is a map that graphically illustrates the distribution of redox potentials. Redox is decreased to values below -200 mV in the vicinity of CPT-03, CPT-06, CPT-09, CPT-14, CPT-26, and CPT-07 in March 1994. As expected, areas at the site with low redox potentials appear to coincide with areas of high BTEX contamination, low DO, slightly elevated ferrous iron concentrations, and elevated methane concentrations (compare Figures 4.2, 4.4, 4.9, 4.10, and 4.12).

4.3.3.7 Alkalinity

Total alkalinity (as calcium carbonate) was measured at groundwater monitoring points and existing monitoring wells in March 1994. These measurements are summarized in Table 4.5. Total alkalinity (as calcium carbonate) also was measured at select groundwater monitoring points in March 1995. These measurements are summarized in Table 4.6. Alkalinity is a measure of a groundwater's ability to buffer changes in pH caused by the addition of biologically generated acids. Total alkalinity at the site is in the low to moderate range for groundwater, and varies from 148 mg/L at CPT-24S to 520 mg/L at CPT-03S (March 1994). This amount of alkalinity should be sufficient to buffer potential changes in pH caused by biologically mediated BTEX oxidation reactions.

4.3.3.8 pH

pH was measured at groundwater monitoring points and existing monitoring wells in March 1994. These measurements are summarized in Table 4.5. pH was measured at select groundwater monitoring points in March 1995. These measurements are summarized in Table 4.6. The pH of a solution is the negative logarithm of the hydrogen ion concentration $[H^+]$. Groundwater pH at Site ST-29 ranges from 6.7 to 7.6 (March 1994). The majority of groundwater samples had a pH of 7.1 to 7.3 (March 1994). This range of pH is within the optimal range for BTEX-degrading microbes.



4.3.3.9 Temperature

Groundwater temperature was measured at groundwater monitoring points and existing monitoring wells in March 1994. Table 4.5 summarizes groundwater temperature readings in March 1994. Groundwater temperature also was measured at select groundwater monitoring points in March 1995. Table 4.6 summarizes groundwater temperature readings in March 1995. Temperature affects the types and growth rates of bacteria that can be supported in the groundwater environment, with higher temperatures generally resulting in higher growth rates. Temperatures in the shallow saturated zone varied from 24.7 degrees Celsius (°C) to 27.8°C. These are relatively high temperatures for shallow groundwater, suggesting that bacterial growth rates could be high.

4.3.3 Expressed Assimilative Capacity

The data presented in the preceding sections suggest that mineralization of BTEX compounds is occurring through the microbially mediated processes of aerobic respiration, iron reduction, and methanogenesis. Based on the stoichiometry presented in these sections, the expressed BTEX assimilative capacity of groundwater at Site ST-29 is at least 18,690 µg/L (March 1994, Table 4.7). The calculations presented in these earlier sections are conservative because they do not account for microbial cell mass production. In addition, the measured concentrations of ferrous iron and methane may not be the maximum achievable. The highest plausible dissolved total BTEX concentration observed at the site in March 1994 was 7,304 µg/L in monitoring point CPT-03S. In March 1995, the highest observed total dissolved BTEX concentration was 14,096 µg/L.

Based on the calculations presented in the preceding sections, and on site observations, groundwater at Site ST-29 has more than sufficient assimilative capacity to degrade dissolved BTEX that partitions from the residual phase into the groundwater before the plume migrates 1,200 feet downgradient from the source area.

TABLE 4.7
EXPRESSED ASSIMILATIVE CAPACITY OF SITE GROUNDWATER
MARCH 1994
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Electron Acceptor or Process	Expressed BTEX Assimilative Capacity (µg/L)
Dissolved Oxygen	1,200
Ferric Hydroxide	90
Methanogenesis	17,400
Expressed Assimilative Capacity	18,690
Highest observed Total BTEX Concentration	7,304

4.4 DIRECT MICROBIOLOGICAL EVIDENCE OF BTEX BIODEGRADATION

USEPA researchers collected groundwater samples for volatile fatty acids (VFAs) analysis in March 1995 at monitoring points CPT-09D, CPT-3M, and CPT-2S. All of these sample locations are within the dissolved BTEX plume. This test is a gas chromatography/mass spectrometry (GC/MS) method wherein the samples are compared to a standard mixture containing a total of 58 phenols, aliphatic acids, and aromatic acids.

During biodegradation of BTEX compounds, VFAs are produced as metabolic byproducts. The production of these VFAs is a direct indication that biodegradation of BTEX compounds is occurring. Table 4.8 shows that propanoic acid, 2-methylpropanoic acid, trimethyl acetic acid, butyric acid, 3,3-dimethylbutyric acid, pentanoic acid, hexanoic acid, 2-ethylhexanoic acid, m-tolylacetic acid, 2,6-dimethylbenzoic acid, 2,5 dimethylbenzoic acid, 3,5-dimethylbenzoic acid, 2,4,6-trimethylbenzoic acid, and 2,4,5 trimethylbenzoic acid all are present in groundwater contaminated with BTEX. This provides additional strong evidence that biodegradation of BTEX is occurring at Site ST-29.

TABLE 4.8
VOLATILE FATTY ACIDS IN GROUNDWATER (1995)
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Compound	Sample Location Sample Name	CPT-09D 86-MW-9D	CPT-3M + 2S 86-MW3M + 2S
Propanoic Acid		34	30
2-Methylpropanoic Acid		6	5
Trimethyl Acetic Acid		8	16
Butyric Acid		12	11
2-Methylbutyric Acid		<5	<5
3-Methylbutyric Acid		<5	<5
3,3-Dimethylbutyric Acid		123	11
Pentanoic Acid		7	5
2,3-Dimethylbutyric Acid		<5	<5
2-Ethylbutyric Acid		ND ^{a/}	ND
2-Methylpentanoic Acid		ND	ND
3-Methylpentanoic Acid		<5	<5
4-Methylpentanoic Acid		ND	<5
Hexanoic Acid		19	13
2-Methylhexanoic Acid		ND	ND
Phenol		<5	<5
Cyclopentanecarboxylic Acid		ND	ND
5-Methylhexanoic Acid		ND	ND
o-Cresol		ND	ND
2-Ethylhexanoic Acid		188	117
Heptanoic Acid		<5	<5
m-Cresol		ND	ND
p-Cresol		ND	ND
1-Cyclopentene-1-Carboxylic Acid		ND	ND
o-Ethylphenol		ND	ND
Cyclopentaneacetic Acid		ND	ND
2,6-Dimethylphenol		ND	ND
2,5-Dimethylphenol		ND	<5
Cyclohexanecarboxylic Acid		ND	ND
3-Cyclohexene-1-Carboxylic Acid		ND	ND
2,4-Dimethylphenol		ND	ND
3,5-Dimethylphenol & m-Ethylphenol		ND	ND
Octanoic Acid		<5	<5
2,3-Dimethylphenol		ND	<5
p-Ethylphenol		ND	ND
Benzoic Acid		5	<5
3,4-Dimethylphenol		ND	ND
m-Methylbenzoic Acid		ND	ND
1-Cyclohexene-1-Carboxylic Acid		ND	ND
Cyclohexaneacetic Acid		ND	ND
2-Phenylpropanoic Acid		ND	ND
o-Methylbenzoic Acid		<5	<5
Phenylacetic Acid		<5	<5
m-Tolylacetic Acid		8	6
o-Tolylacetic Acid		ND	10
2,6 -Dimethylbenzoic Acid		13	10
p-Tolylacetic Acid		ND	<5
p-Methylbenzoic Acid		ND	<5
3-Phenylpropanoic Acid		ND	ND
2,5 -Dimethylbenzoic Acid		49	13
Decanoic Acid		<5	<5
2,4 -Dimethylbenzoic Acid		<5	<5
3,5 -Dimethylbenzoic Acid		<5	ND
2,3 -Dimethylbenzoic Acid		16	19
4-Ethylbenzoic Acid		ND	ND
2,4,6-Trimehtylbenzoic Acid		75	122
3,4-Dimethylbenzoic Acid		ND	<5
2,4,5-Trimehtylbenzoic Acid		84	26

All data in parts per billion (ppb).

a/ ND = compound not detected.

SECTION 5

GROUNDWATER MODEL

5.1 GENERAL OVERVIEW AND MODEL DESCRIPTION

In order to help estimate degradation rates for dissolved BTEX compounds at Site ST29 and to help predict the future migration of these compounds, Parsons ES modeled the fate and transport of the dissolved BTEX plume. The modeling effort had three primary objectives: 1) to predict the future extent and concentration of the dissolved contaminant plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation; 2) to assess the potential for downgradient receptors to be exposed to contaminants at concentrations above levels of regulatory concern; and 3) to provide technical support for the natural attenuation remedial option at post-modeling regulatory negotiations. The model was developed using site-specific data and conservative assumptions about governing physical and chemical processes. Because of the conservative nature of model input, the reduction in contaminant mass caused by natural attenuation is expected to exceed model predictions. This analysis is not intended to represent a baseline assessment of potential risks posed by site contamination.

The Bioplume II code was used to estimate the potential for dissolved BTEX migration and degradation by naturally occurring mechanisms operating at Site ST-29. The Bioplume II model incorporates advection, dispersion, sorption, and biodegradation to simulate contaminant plume migration and degradation. The model is based upon the USGS Method of Characteristics (MOC) two-dimensional (2-D) solute transport model of Konikow and Bredehoeft (1978). The model was modified by researchers at Rice University to include a biodegradation component that is activated by a superimposed DO plume. Based on the work of Borden and Bedient (1986), the model assumes a reaction between the DO and BTEX that is instantaneous relative to the advective groundwater velocity. Bioplume II solves the USGS 2-D solute transport equation twice, once for hydrocarbon concentrations in the aquifer and once for a DO plume. The two plumes are combined using superposition at every particle move to simulate the instantaneous, biologically-mediated, reaction between hydrocarbons and oxygen.

In recent years it has become apparent that anaerobic processes such as nitrate reduction (denitrification), iron reduction, sulfate reduction, and methanogenesis can be important BTEX degradation mechanisms (Grbic'-&alic', 1990; Beller *et al*, 1992; Edwards *et al.*, 1992; Edwards and Grbic'-Galic', 1992, Grbic'-Galic' and Vogel, 1987; Lovely *et al*, 1989; Hutchins, 1991). Although there is evidence that anaerobic biodegradation of fuel hydrocarbons is occurring at Site ST-29, these processes were not accounted for during the modeling. Limiting the simulation to oxygen-limited degradation is a conservative assumption intended to prevent overestimation of degradation rates. The following subsections discuss in more detail the model setup, input parameters and assumptions, model calibration, and simulation results.

5.2 CONCEPTUAL MODEL DESIGN AND ASSUMPTIONS

Prior to developing a groundwater model, it is important to determine if sufficient data are available to provide a reasonable estimate of aquifer conditions. In addition, it is important to ensure that any limiting assumptions can be justified. The most important assumption made when using the Bioplume II model is that oxygen-limited biodegradation is occurring at the site. The Bioplume II model assumes that the limiting factors for biodegradation are: 1) the presence of an indigenous hydrocarbon degrading microbial population, and 2) sufficient background electron acceptor concentrations. Data and information presented in Sections 3 and 4 suggest that oxygen, ferric hydroxide, and carbon dioxide (methanogenesis) are being used as electron acceptors for aerobic and anaerobic biodegradation at Site ST-29. To be conservative, only oxygen was considered as an electron acceptor in the Bioplume II model presented herein. To model biodegradation of BTEX with DO as an electron acceptor, the isopleth maps for these compounds were superimposed on the model grid. Data from this map then were used for model input.

Based on the data presented in Section 3, the shallow saturated zone was conceptualized and modeled as a shallow unconfined aquifer comprised of fine to coarse sand with some gravel or shell fragments (Figures 3.3 and 3.4). The use of a 2-D model is appropriate at Site ST-29 because the saturated interval is relatively homogenous and water level data indicate that the local flow system as defined by horizontal and vertical gradients will likely prevent significant vertical migration of dissolved contamination.

Bioventing has been implemented in the area of greatest soil contamination (north of the car wash). Bioventing will further reduce the residual LNAPL which is the source of continuing dissolved BTEX contamination at the site. After calibration, one of the predictive contaminant fate and transport simulations assumed BTEX source reduction as a result of bioventing.

5.3 INITIAL MODEL SETUP

Where possible, the initial setup for this model was based on existing site data. Where site-specific data were not available, reasonable assumptions for the types of materials comprising the shallow saturated zone were made based on widely accepted literature values. The following sections describe the basic model setup. Those Bioplume II model parameters that were varied during model calibration are discussed in Section 5.4.

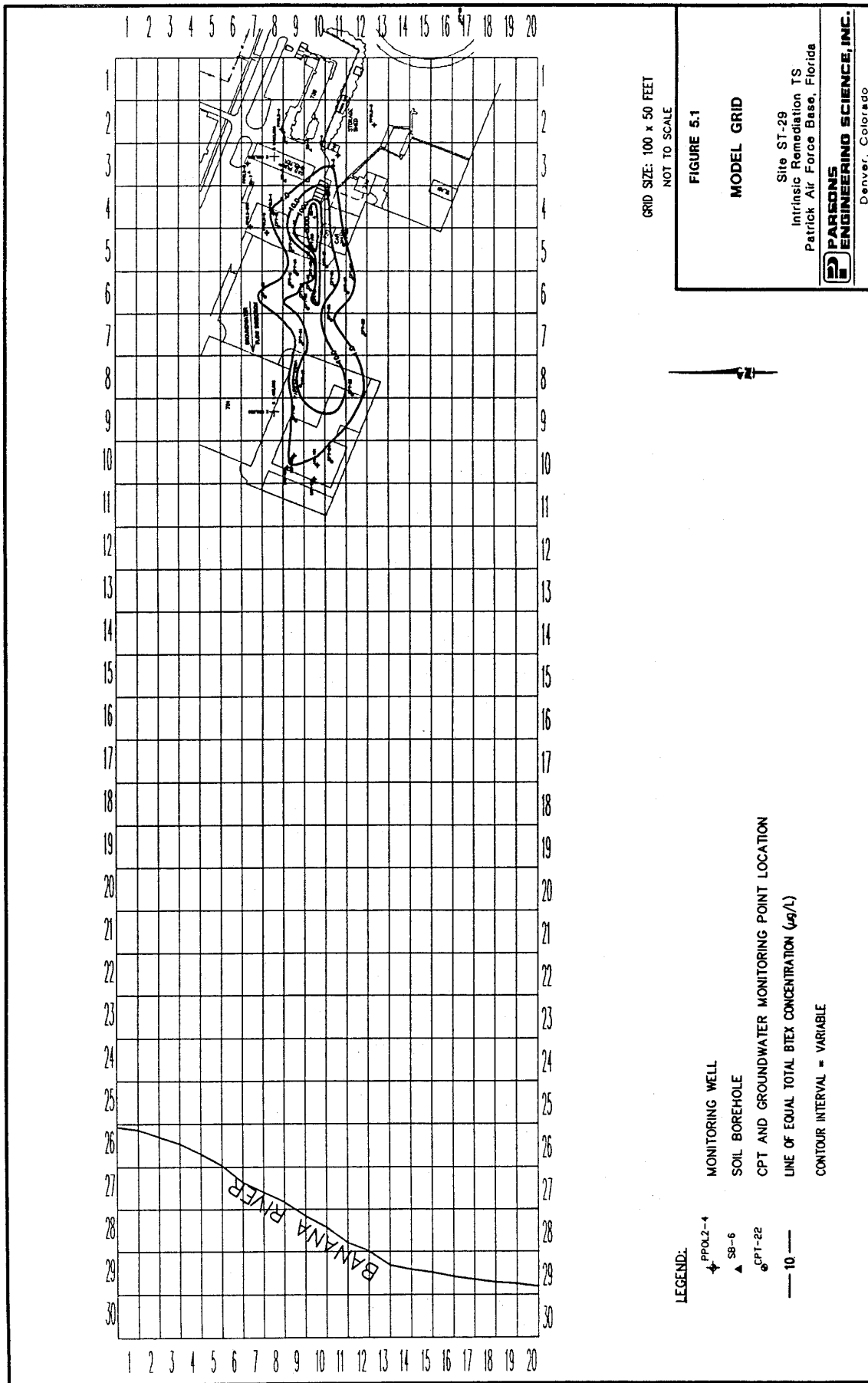
5.3.1 Grid Design and Boundary Conditions

The maximum grid size for the Bioplume II model is limited to 20 columns by 30 rows. The dimension of each column and row can range from 0.1 to 999.9 feet. A 20- by 30-cell grid was used to model the Patrick AFB site. Each grid cell was 100 feet long by 50 feet wide. The grid was oriented so that the longest dimension was parallel to the overall direction of groundwater flow. The model grid covers an area of 3 million square feet, or approximately 69 acres. The full extent of the model grid is indicated on Figure 5. 1.

Model boundaries are mathematical statements that represent hydrogeologic boundaries, such as areas of specified head (e.g., surface water bodies or contour lines of constant hydraulic head) or specified flux. Hydrogeologic boundaries are represented by three mathematical statements that describe the hydraulic head at the model boundaries. These include:

- 1) Specified-head boundaries (Dirichlet condition) for which the head is determined as a function of location and time only. Surface water bodies exhibit constant head conditions. Specified-head boundaries are expressed mathematically as:

$$Head = f(x, y, z, t)$$



- 2) Specified-flow boundaries (Neumann conditions) for which the mathematical description of the flux across the boundary is given. The flux is defined as a volumetric flow rate per unit area (e.g., ft³/ft²/day). No-flow boundaries are a special type of specified-flow boundary and are set by specifying the flux to be zero. Examples of no-flow boundaries include groundwater divides and impermeable hydrostratigraphic units. Specific-flux boundaries are expressed mathematically as:

$$Flux = f(x,y,z,t)$$

- 3) Head-dependent flow boundaries (Cauchy or mixed-boundary conditions) where the flux across the boundary is calculated from a given boundary head value. This type of flow boundary is sometimes referred to as a mixed-boundary condition because it is a combination of a specified-head boundary and a specified-flow boundary. Head-dependent flow boundaries are used to model leakage across semipermeable boundaries. Head-dependent flow boundaries are expressed mathematically as (Bear, 1979):

$$Flux = \frac{(H_0 - H)k}{B'}$$

Where: H = Head in the zone being modeled (generally the zone containing the contaminant plume)
H₀ = Head in external zone (separated from plume by semipermeable layer)
K' = Hydraulic conductivity of semipermeable layer
B' = Thickness of semipermeable layer

Natural hydraulic boundaries are modeled using a combination of the three types of model boundary conditions listed above. When possible, hydrologic boundaries such as surface water bodies, groundwater divides, contour lines, or hydrologic barriers should coincide with the perimeter of the model. In areas lacking obvious hydrologic boundaries, specified-head or specified-flux boundaries can be specified at the model perimeter if the boundaries are far enough removed from the contaminant plume that transport calculations are not affected. Bioplume II requires the entire model domain to be bounded by zero-flux cells (also known as no-flow cells), with other boundary conditions established within the subdomain specified by the no-flow cells.

Specified-head boundaries for the model were set on the eastern and western perimeter of the model grid to simulate the westward flow of groundwater observed at the site. The eastern boundary was set in the approximate location of the groundwater divide indicated by water level data. The head of this boundary was estimated to be 2.3 to 2.4 feet above msl. The western model boundary was defined by the eastern bank of the Banana River, which runs north-northeast along the western edge of the Base. The head of the river was assumed to be 0.1 foot above msl. These constant-head cells were placed far enough away from the BTEX plume to avoid potential boundary interferences.

The northern and southern model boundaries were left as no-flow boundaries. In this case, the flux through these boundaries is assumed to be zero because flow is parallel to these boundaries. The base, or lower, boundary of the model is also assumed to be no flow. The upper model boundary is defined by the simulated water table surface.

5.3.2 Groundwater Elevation and Gradient

The 1994 water table elevation map presented in Figure 3.5 was used to define the starting heads input into the Bioplume II model. Groundwater flow in the vicinity of Site ST-29 is to the west with an average gradient of approximately 0.002 ft/ft between monitoring points CPT-03 and CPT-24. It is likely that the gradient diminishes to the west; if the observed gradient (0.002 ft/ft) extended all the way to the Banana River (approximately 2,000 feet west of CPT-24), the water table would be 2 to 3 feet below msl. No data are available to quantify seasonal variations in groundwater flow direction or gradient at the site; it was assumed that the observed water levels were representative of steady-state conditions. As described in Section 5.4.1, the model was calibrated to the observed water table.

The area of study is effectively isolated from any tidal influences. A groundwater divide is present just east of the site is between the modeled area and the Atlantic Ocean. In addition, there are no measurable tides along the Banana River which is located on the same side of the groundwater divide as the ST-29 BTEX plume (this is indicated on the USGS topographic maps for the site and vicinity). Furthermore, a study by Bredehoeft (1967) indicates that tides have a minor influence on groundwater levels, producing fluctuations on the order of 1 to 2 centimeters, even in areas with significant (3 feet or greater) tidal fluctuations.

5.3.3 BTEX Concentrations

The total dissolved BTEX concentrations obtained from 1994 laboratory analytical data for each CPT and well location were used for model development (Table 4.3). At CPT nests, the highest BTEX concentration from all monitoring points at that location was used. The observed BTEX plume covers an area of approximately 90,000 square feet (2 acres). The shape and distribution of the total BTEX plume is the result of advective-dispersive transport and biodegradation of dissolved BTEX contamination. As described in Section 5.4.2, the simulated BTEX plume was calibrated to match the observed BTEX plume.

5.3.4 Dissolved Oxygen

As discussed previously, the Bioplume II model assumes an instantaneous reaction between the BTEX plume and the DO plume. The discussion presented in Section 4 suggests that DO, ferric iron, and carbon dioxide (for methanogenesis) are being used as electron acceptors for biodegradation of BTEX compounds at Site ST-29. To be conservative, the total BTEX plume at Site ST-29 was modeled assuming that DO was the only electron acceptor being utilized for the biodegradation of the BTEX compounds.

Groundwater samples collected in uncontaminated portions of the aquifer suggest that background DO concentrations at the site are as high as 3.7 mg/L. To be conservative, background oxygen concentrations were assumed to be 3.5 mg/L for Bioplume II model development. Table 4.4 contains DO data for the site. Figures 4.4 and 4.5 are DO isopleth maps.

The upgradient constant-head cells in the Bioplume II model require background electron acceptor concentrations to be input as constant concentrations to simulate incoming electron acceptors. A DO concentration of 3.5 mg/L (as measured at crossgradient point CPT-25) was used for these cells.

5.4 MODEL CALIBRATION

Model calibration is an important component in the development of any numerical groundwater model. Calibration of the flow model demonstrates that the model is capable of matching hydraulic conditions observed at the site; calibration of a contaminant transport model superimposed upon the calibrated flow model helps verify that

contaminant loading and transport conditions are being appropriately simulated. The numerical flow model presented herein was calibrated by altering transmissivity in a trial-and-error fashion until simulated heads approximated observed field values within a prescribed accuracy. After calibration of the flow model, the numerical transport model was calibrated by altering hydraulic parameters, transport parameters, and stresses (i.e., injection wells and their contaminant loading rates) in a trial-and-error fashion until the simulated BTEX plume approximated observed field values. Table 5.1 Lists input parameters used for the modeling effort. Model input and output is included in Appendices C and D, respectively.

5.4.1 Water Table Calibration

The shallow water table at Site ST-29 was assumed to be influenced only by continuous recharge and discharge at the constant-head cells established at the upgradient and downgradient model boundaries. Recharge of the aquifer through rainfall was not included in the model. This is considered appropriate because a large portion of the contaminated area is covered by concrete. Potential recharge from other sources was omitted because of a lack of reliable data. Only the initial water levels at the constant head cells and the transmissivity were varied to calibrate the water table surface. The model was calibrated under steady-state conditions.

Hydraulic conductivity is an important aquifer characteristic that determines the ability of the water-bearing strata to transmit groundwater. Transmissivity is the product of the hydraulic conductivity and the thickness of the aquifer. An accurate estimate of hydraulic conductivity is important to help quantify advective groundwater flow velocities and to define the flushing potential of the aquifer and the quantity of electron-acceptor-charged groundwater that is entering the site from upgradient locations. Based on the work of Rifai *et al.* (1988), the Bioplume II model is particularly sensitive to variations in hydraulic conductivity. Lower values of hydraulic conductivity result in a slower-moving plume that degrades at a slower rate because less oxygen, nitrate, iron, sulfate, and carbon dioxide are available for biodegradation. Higher values of hydraulic conductivity result in a faster moving plume that degrades faster because more electron acceptors are available for biodegradation.

TABLE 5.1
BIOPLUME II MODEL INPUT PARAMETERS
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Parameter	Description	Calibrated Model Setup	PATC	PATD
NTIM	Maximum number of time steps in a pumping period	8	58	34
NPMP	Number of Pumping Periods	1	1	4
NX	Number of nodes in the X direction	20	20	20
NY	Number of nodes in the Y direction	30	30	30
NPMAX	Maximum number of Particles $NPMAX = (NX-2)(NY-2)(NPTPND) + (Ns^*) (NPTPND) + 250$	5250	5250	5250
NPNT	Time step interval for printing data	1	1	1
NITP	Number of iteration parameters	7	7	7
NUMOBS	Number of observation points	0	0	0
ITMAX	Maximum allowable number of iterations in ADIP ^u	200	200	200
NREC	Number of pumping or injection wells	5	5	5
NPTPND	Initial number of particles per node	9	9	9
NCODES	Number of node identification codes	3	3	3
NPNTMV	Particle movement interval (IMOV)	0	0	0
NPNTVL	Option for printing computed velocities	2	2	2
NPNTD	Option to print computed dispersion equation coefficients	2	0	0
NPDEL	Option to print computed changes in concentration	0	0	0
NPCHV	Option to punch velocity data	0	0	0
NREACT	Option for biodegradation, retardation and decay	1	1	1
PINT	Pumping period (years)	8	58	8,1,1,25
TOL	Convergence criteria in ADIP	0.001	0.001	0.001
POROS	Effective porosity	0.35	0.35	0.35
BETA	Characteristic length (long. dispersivity; feet)	20	20	20
S	Storage Coefficient	0 (Steady-State)	0	0
TIMX	Time increment multiplier for transient flow	-	-	-
TINIT	Size of initial time step (seconds)	-	-	-
XDEL	Width of finite difference cell in the x direction (feet)	50	50	50
YDEL	Width of finite difference cell in the y direction (feet)	100	100	100
DLTRAT	Ratio of transverse to longitudinal dispersivity	0.3	0.3	0.3
CELDIS	Maximum cell distance per particle move	0.5	0.5	0.5
ANFCTR	Ratio of T _{yy} to T _{xx} (1 = isotropic)	1	1	1
DK	Distribution coefficient	0.35	0.35	0.35
RHOB	Bulk density of the solid (grams/cubic centimeter)	1.6	1.6	1.6
THALF	Half-life of the solute	-	-	-
DEC1	Anaerobic decay coefficient	0	0	0
DEC2	Reaeration coefficient (day ⁻¹)	0.0009	0.0009	0.0009
F	Stoichiometric Ratio of HC to Oxygen	3.1	3.1	3.1

^{**} Ns = Number Of Nodes That Represent Fluid Sources (Wells or Constant Head Cells)

^u ADIP = Alternating-Direction Implicit Procedure (subroutine for solving groundwater flow equation)

Saturated thickness data from previous reports, CPT logs, and water level measurements were used in conjunction with the average hydraulic conductivity as determined from slug tests (0.052 ft/min) to estimate an initial uniform transmissivity for the entire model domain. Based on slug tests performed at the site, hydraulic conductivity varies from 9.6×10^{-3} ft/min to 8.9×10^{-2} ft/min and is within the accepted range for sandy materials (Freeze and Cherry, 1979). To better match heads in the model to observed

values, the transmissivities were progressively varied in blocks and rows until the simulated water levels for cells corresponding to the selected well locations matched the observed water levels as closely as possible. Figure 5.2 shows the calibrated water table. Calibrated model hydraulic conductivities ranged from 3.0×10^{-2} ft/min to 0.14 ft/min (5.0×10^{-4} feet per second (ft/sec) to 2.3×10^{-3} ft/sec).

Water level elevation data from eight monitoring well and monitoring point locations were used to compare measured and simulated heads for calibration. The eight selected locations were: CPT-03, CPT-04, CPT-18, CPT-21, CPT-22, CPT-23, CPT-24, and PPOL2-1.

The root mean squared (RMS) error is commonly used to express the average difference between simulated and measured heads. RMS error is the average of the squared differences between measured and simulated heads, and can be expressed as:

$$\text{RMS} = \left[\frac{1}{n} \sum_{i=1}^n (h_m - h_s)_i^2 \right]^{0.5}$$

Where: n = the number of points where heads are being compared

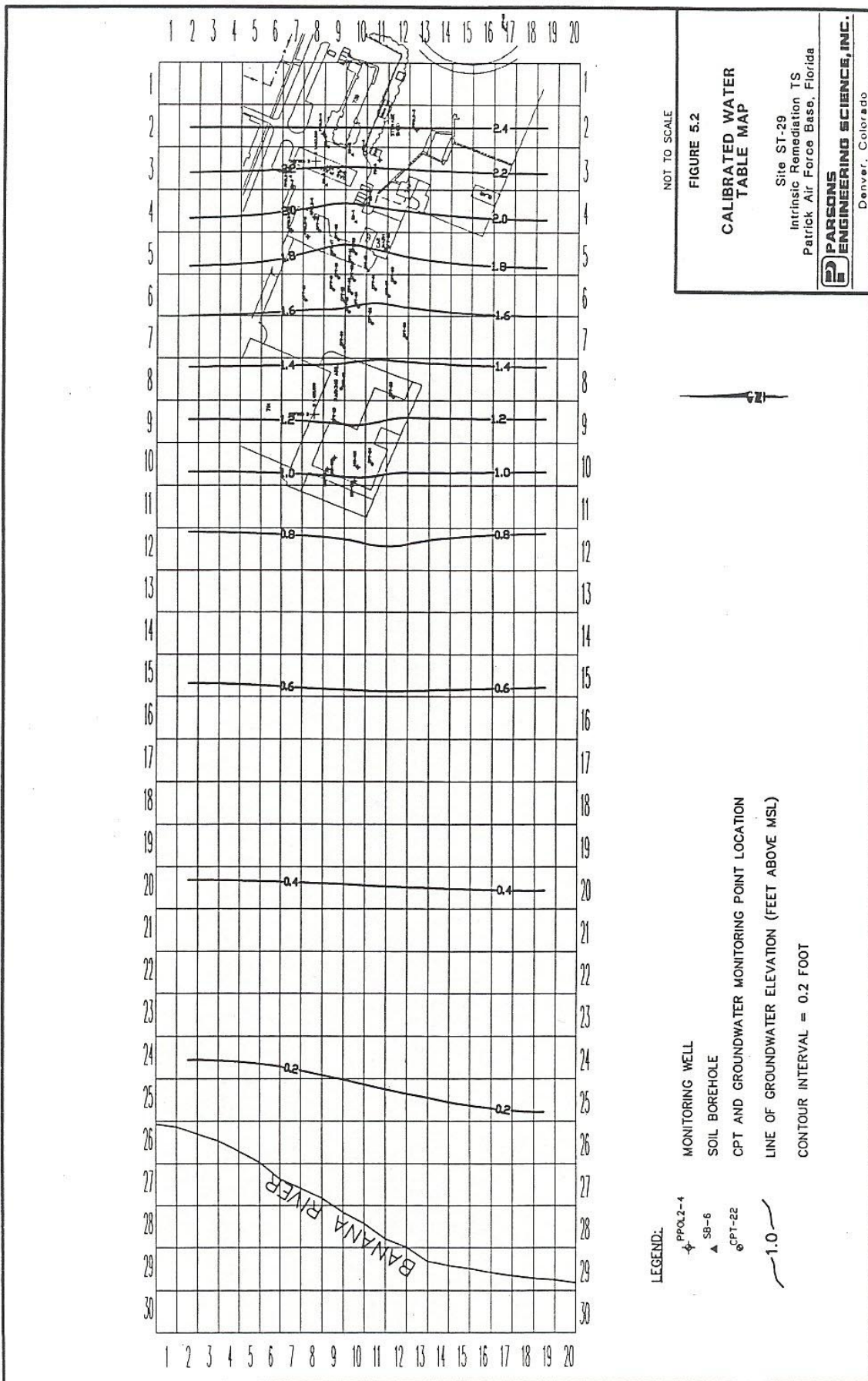
h_m = measured head value

h_s = simulated head value.

The RMS error between observed and calibrated values at the eight comparison points was 0.091 foot, which corresponds to a calibration error of 3.97 percent (water levels dropped 2.3 feet over the length of the model grid). RMS error calculations are summarized in Appendix C. A plot of measured vs calibrated heads shows a random distribution of points and is also shown in Appendix C. Deviation of points from a straight line should be randomly distributed in a plot of results from computer simulations (Anderson and Woessner, 1992).

In solving the groundwater flow equation, Bioplume II establishes the water table surface and calculates an overall hydraulic balance that accounts for the numerical difference between flux into and out of the system. The hydraulic mass balance for the calibrated model was excellent, with 99.9 percent of the water flux into and out of the system being numerically accounted for (i.e., a 0.1-percent error). According to Anderson and Woessner (1992), a mass balance error of around

1 percent is acceptable, while Konikow (1978) indicates an error of less than 0.1 percent was ideal.



5.4.2 BTEX Plume Calibration

Model input parameters affecting the distribution and concentration of the simulated BTEX plume were modified so that model predictions matched dissolved total BTEX concentrations observed in March 1994. To do this, model runs were made using the calibrated steady-state hydraulic parameters coupled with the introduction of contaminants. For this site, the calibration also involved a time element, because it is known that fuel was released in 1985 or 1986. As a result, the plume calibration simulations were made with a time constraint of 8 years; in other words, computed BTEX plume concentrations and configurations were compared to March 1994 data after 8 years of simulation time incorporating the initial introduction of contaminants into the groundwater.

Because residual LNAPL contamination is present in the vicinity of the water table at the site, it was necessary to include injection wells to simulate partitioning of BTEX compounds from the residual LNAPL into the groundwater. The location of the injection wells is shown on Figure 5.3. Locations of injection wells were based on the extent of soil contamination as indicated on Figure 4.1, the extent of groundwater contamination indicated on Figure 4.2, and the approximate location of the former UST and product line that were known to leak.

While the term “injection well” suggests contaminants are being introduced at a point, Bioplume II assumes that contamination introduced at a well instantly equilibrates throughout the entire cell in which the well is located. The injection rate for the cells was set at $1 \times 10^{-5} \text{ ft}^3/\text{sec}$, a value low enough so that the flow calibration and water balance were not affected. Relatively high BTEX concentrations were injected in upgradient injection wells because of the low pumping rate and the influx of oxygen introduced at the upgradient constant-head cells. Replenishment of oxygen quickly degraded BTEX concentrations at the head of the plume, which in turn required larger injection concentrations of BTEX to produce observed BTEX contours. It was assumed that the initial DO concentration in the shallow aquifer was uniformly 3.5 mg/L, and that water with that DO concentration would be continually introduced at the eastern grid boundary.

Total BTEX injection concentrations were determined by varying the injection concentration for the various wells from 100 to 1,500 mg/L until the modeled total BTEX plume approximated the total BTEX plume observed in March 1994. By varying the injection well concentrations, the coefficient of retardation, dispersivity, and the

reaeration coefficient, the BTEX plume was calibrated reasonably well to the existing plume. The calibrated plume configuration is shown on Figure 5.4.

The calibrated model plume, while not identical to the observed BTEX plume, compares very favorably. The computed plume does not have concentrations as high as the concentration observed at CPT-03 (7,304 $\mu\text{g/L}$), but the area of the computed 3,200 $\mu\text{g/L}$ BTEX contour roughly coincides with the 5,000 $\mu\text{g/L}$ contour interpreted from the observed concentrations. The maximum simulated concentration was 3,500 $\mu\text{g/L}$ for the cell just upgradient from CPT-03. The computed distribution likely represents a similar total mass of BTEX, because the model assumes that contamination extends throughout the total depth of the aquifer, while in reality the plume is only present in a portion of the total aquifer thickness (Figure 4.3). In addition, the horizontal extent of the computed 1,600- $\mu\text{g/L}$ contour compares favorably with the observed 1,000- $\mu\text{g/L}$ contour. Finally, the computed 50- $\mu\text{g/L}$ contour delineates an area similar to the area delineated by the observed 10- $\mu\text{g/L}$ contour. Comparison with the observed 5.0- and 1.0- $\mu\text{g/L}$ contours is not possible because the model output did not include concentrations low enough to allow contouring at a similar level. The apparent discrepancies between observed BTEX concentrations and those predicted by the model result from use of a discretized grid to model a continuous system and from the output of the model, in which simulated reported contaminant concentrations are averages for each entire model cell. Because of the conservative assumptions made in constructing the model and selecting parameters, the model results are conservative and are not likely to underestimate contaminant travel distances.

5.4.2.1 Discussion of Parameters Varied During Plume Calibration

As noted previously, the transport parameters varied during plume calibration were dispersivity, the coefficient of retardation, and the coefficient of reaeration. These parameters were generally varied with the intent of limiting plume migration to the observed extents, because the original estimates for the parameters resulted in a calculated BTEX plume that extended almost twice as far as the observed plume. While these parameters were varied with this common intent, each had a slightly different impact on the size and shape of the simulated plume. BTEX concentrations in the simulated injection wells also were varied, but these parameters had little effect on plume size and shape unless they were too low to permit the plume to migrate beyond the source cells or so high that the simulated concentrations were unrealistic.

5. 4. 2.1.1 *Effective Porosity*

Effective porosity plays a significant role in calculations of groundwater velocity, which will in turn affect the simulation of contaminant transport. As noted in Section 3.3.3.3, the effective porosity of the aquifer materials at Site ST-29 was assumed to be 35 percent. This value was not changed during calibration.

5.4.2. 1.2 *Dispersivity*

Much controversy surrounds the concepts of dispersion and dispersivity. Longitudinal dispersivity values for sediments similar to those found at the site range from 0.1 to 200 feet (Walton, 1988). Longitudinal dispersivity was originally estimated as 17 feet, using one-tenth of the distance between the spill source and the longitudinal centroid of the plume. Dispersivity estimation calculations are included in Appendix C. Transverse dispersivity values generally are estimated as one-tenth (0.1) of the longitudinal dispersivity values (Domenico and Schwartz, 1990). The initial model input assumed the same ratio.

During plume calibration, longitudinal dispersivity was increased to 20 feet from the original estimate of 17 feet. In addition, the ratio of transverse dispersivity to longitudinal dispersivity was increased to 0.3 from the original estimate of 0.1. This was done to increase the lateral extent of the plume and to prevent the computed plume from extending too far downgradient, as well as to prevent concentrations in the source cells from being significantly greater than the observed concentrations.

5.4.2.1.3 *Coefficient of Retardation*

Retardation of the BTEX compounds relative to the advective velocity of the groundwater occurs when BTEX molecules are sorbed to the aquifer matrix. Based on measured TOC concentrations in uncontaminated portions of the shallow saturated zone, and assuming a bulk density of 1.6 grams/cubic centimeter (Freeze and Cherry, 1979), and published values of the soil sorption coefficient (K_{oc}) for the BTEX compounds (as listed in Wiedemeier *et al.*, 1995), the coefficients of retardation for the BTEX compounds were calculated. The results of these calculations are summarized in Table 5.2. To be conservative, the range of coefficients of retardation calculated for benzene (1.09 to 3.02) was used as a constraint for model input. The

coefficient of retardation originally input to the model was 1.7. The lower the assumed coefficient of retardation, the farther the BTEX plume will migrate downgradient.

TABLE 5.2
CALCULATION OF RETARDATION COEFFICIENTS
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Compound	K_{oc} (L/kg ^{a/})	Maximum Fraction Organic Carbon ^{b/}	Minimum Fraction Organic Carbon ^{b/}	Average Fraction Organic Carbon ^{b/}	Distribution Coefficient, K_d (L/kg)			Bulk Density (kg/L) ^{d/}	Effective Porosity ^{d/}	Coefficient of Retardation	
					Maximum ^{c/}	Minimum ^{c2/}	Average ^{c3/}			Maximum	Minimum Average
Benzene	79	0.00558	0.00026	0.00143	0.441	0.021	0.113	1.60	0.35	3.02	1.09 1.52
Toluene	190	0.00558	0.00026	0.00143	1.060	0.049	0.272	1.60	0.35	5.85	1.23 2.24
Ethylbenzene	468	0.00558	0.00026	0.00143	2.611	0.122	0.669	1.60	0.35	12.94	1.56 4.06
m-Xylene	405	0.00558	0.00026	0.00143	2.260	0.105	0.579	1.60	0.35	11.33	1.48 3.65
o-Xylene	422	0.00558	0.00026	0.00143	2.355	0.110	0.603	1.60	0.35	11.76	1.50 3.76
p-Xylene	357	0.00558	0.00026	0.00143	1.992	0.093	0.511	1.60	0.35	10.11	1.42 3.33

NOTES:

^{a/} From technical protocol (Wiedemeier *et al.*, 1995).

^{b/} From site data.

^{c1/} K_d = Maximum Fraction Organic Carbon x K_{oc} .

^{c2/} K_d = Minimum Fraction Organic Carbon x K_{oc} .

^{c3/} K_d = Average Fraction Organic Carbon x K_{oc} .

^{d/} Literature values.

During plume calibration, the coefficient of retardation was gradually raised from the initial value of 1.7 to a value of 2.6. As with the dispersivity, this variable was altered in response to model predictions of BTEX concentrations extending well beyond the observed limits. In addition, increasing the value of this parameter also was necessary to increase BTEX concentrations near the source area by limiting the travel rate of the contaminants. By limiting the travel rates, the main body of the plume were exposed to a smaller volume of oxygenated water, resulting in higher simulated concentrations. In addition, organic matter was observed in the vicinity of the water table at several locations. This is significant because hydrophobic organic molecules, such as fuel hydrocarbons, will sorb most readily to organic matter.

5.4.2.1.4 Reaeration Coefficient

The reaeration coefficient is a first-order rate constant used by Bioplume II to simulate the replenishment of oxygen into the groundwater by soil gas diffusion and rainwater infiltration. A reaeration coefficient of 0.003 day^{-1} was originally estimated, based on other documented Bioplume modeling efforts (e.g., Rifai *et al.*, 1988).

The reaeration coefficient had a significant effect on limiting plume migration, but was most important in controlling the BTEX concentrations at the fringes of the plume. At its originally estimated value of 0.003 day^{-1} , the plume did not extend more than one cell length beyond the source cells, and computed concentrations all were greater than $150 \mu\text{g/L}$. This coefficient was reduced to 0.0009 day^{-1} , and the calculated plume extent was more realistic, with computed concentrations below $50 \mu\text{g/L}$ allowing better definition of the plume. Reduction of this coefficient also was appropriate because much of the plume area is covered with concrete, limiting infiltration of oxygenated precipitation.

5.5 SENSITIVITY ANALYSIS

The purpose of the sensitivity analysis is to determine the effect of varying model input parameters on model output. Based on the work of Rifai *et al.* (1988), the Bioplume II model is most sensitive to changes in the coefficient of reaeration, the coefficient of anaerobic decay, and the hydraulic conductivity of the media, and is less sensitive to changes in the retardation factor, porosity, and dispersivity. Because the coefficient of anaerobic decay was set to zero, the

sensitivity analysis was conducted by varying transmissivity, dispersivity, the coefficient of retardation, and the coefficient of reaeration. The use of an anaerobic decay coefficient was rejected because only aerobic biodegradation was modeled for this site.

To perform the sensitivity analyses, an individual run of the plume calibration model was made with the same input as the calibrated model, except that one of the aforementioned parameters was varied. The models were run for 8 years, as was the calibrated model, so that the independent effect of each variable could be assessed. As a result, eight sensitivity runs of the calibrated model were made, with the following variations:

- 1) Transmissivity uniformly increased by a factor of 5;
- 2) Transmissivity uniformly decreased by a factor of 5;
- 3) Longitudinal dispersivity increased by a factor of 5;
- 4) Longitudinal dispersivity decreased by a factor of 5;
- 5) Reaeration coefficient increased by a factor of 5;
- 6) Reaeration coefficient decreased by a factor of 5;
- 7) Coefficient of retardation increased by a factor of 1.5; and
- 8) Coefficient of retardation decreased by a factor of 2.

The results of the sensitivity analyses are shown graphically in Figures 5.5, 5.6, 5.7, and 5.8. These figures display the modeled BTEX concentrations versus distance along the centerline of the plume (in the tenth model column). This manner of displaying data is useful because BTEX concentrations are highest in the tenth column, the plume is relatively narrow, and the plume migrates in a direction parallel to the model grid. Furthermore, the figures allow easy visualization of the changes in BTEX concentration caused by varying model input parameters.

The effects of varying transmissivity are shown by Figure 5.5. Uniformly increasing the transmissivity by a factor of five increased the biodegradation rate of the plume such that the maximum concentrations in the source cell area were only about 150 µg/L, compared to the observed maximum of 7,403 µg/L and the simulated maximum of 3,500 µg/L. In addition, BTEX

were only present in the source cells. This results from the greater flux of water through the model area bringing a greater mass of DO into contact

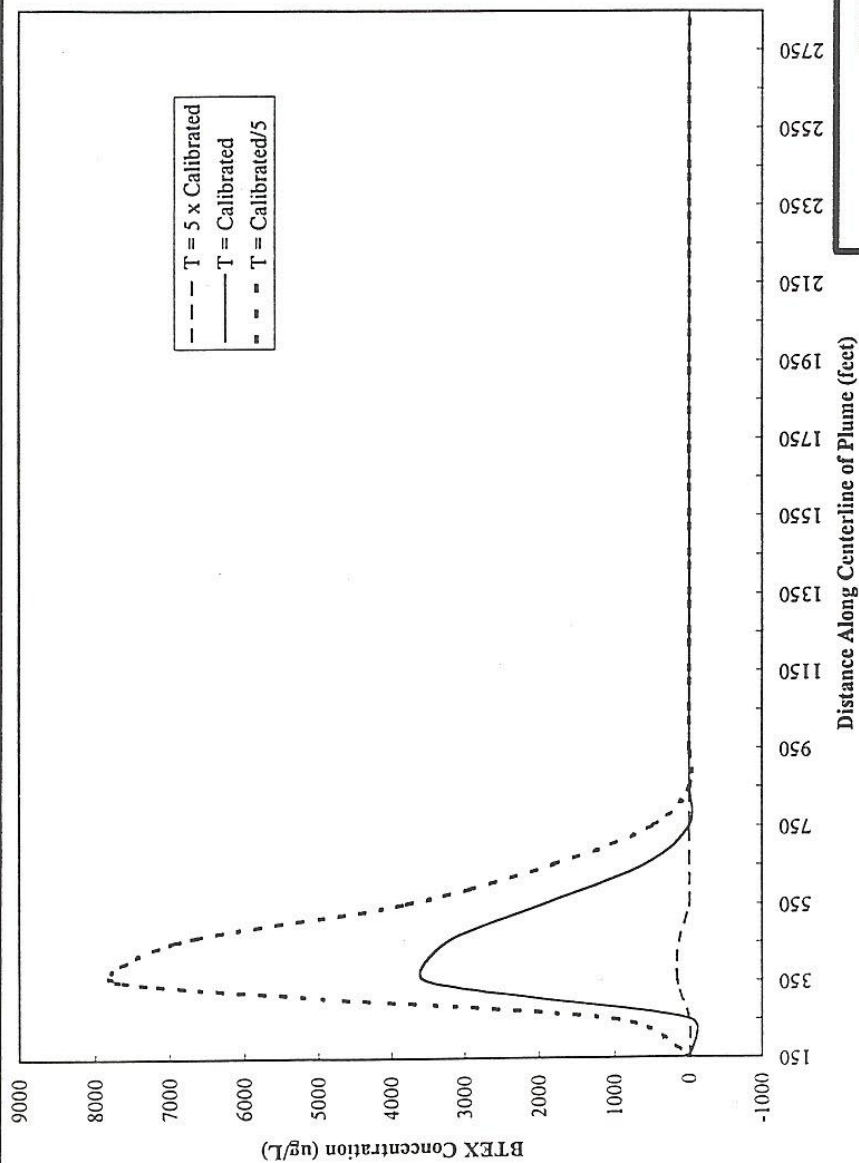


FIGURE 5.5

**MODEL SENSITIVITY
TO VARIATIONS
IN TRANSMISSIVITY**

Site ST-29
Intrinsic Remediation TS
Patrick Air Force Base, Florida

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

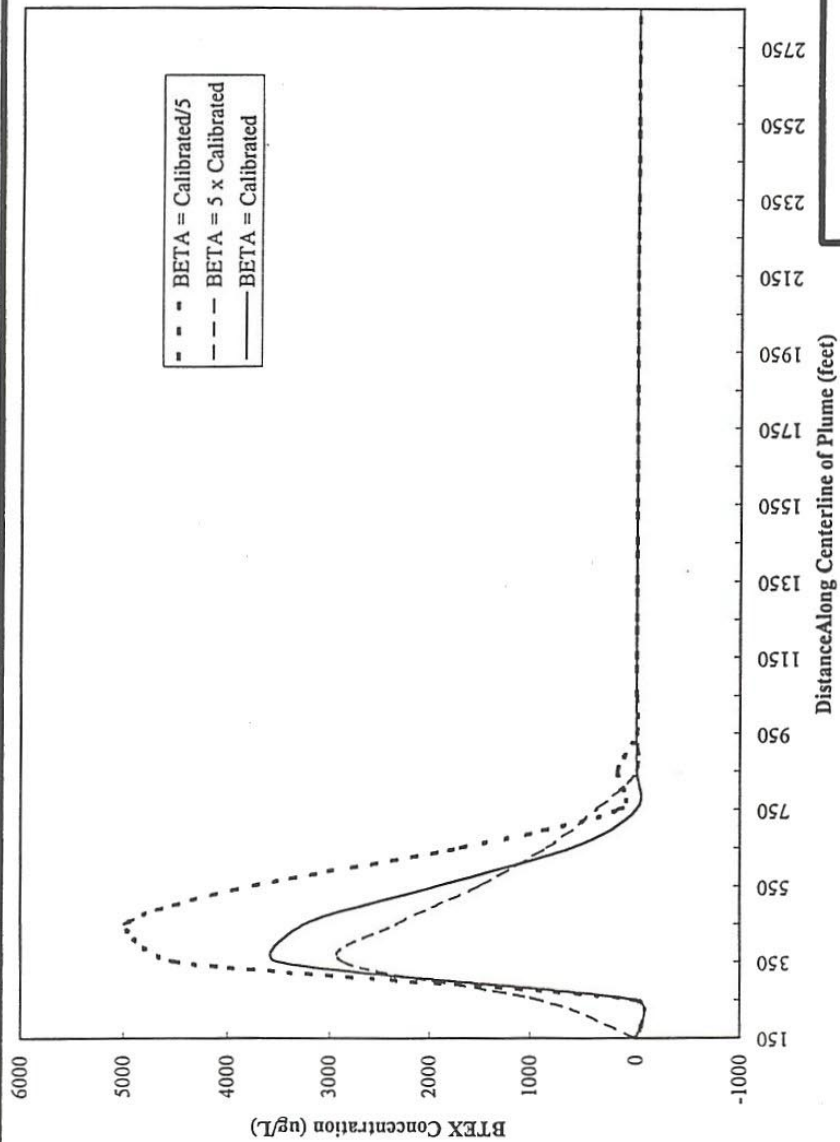


FIGURE 5.6
MODEL SENSITIVITY
TO VARIATIONS
IN DISPERSIVITY

Site ST-29
 Intrinsic Remediation TS
 Patrick Air Force Base, Florida

PARSONS
ENGINEERING SCIENCE, INC.

Denver, Colorado

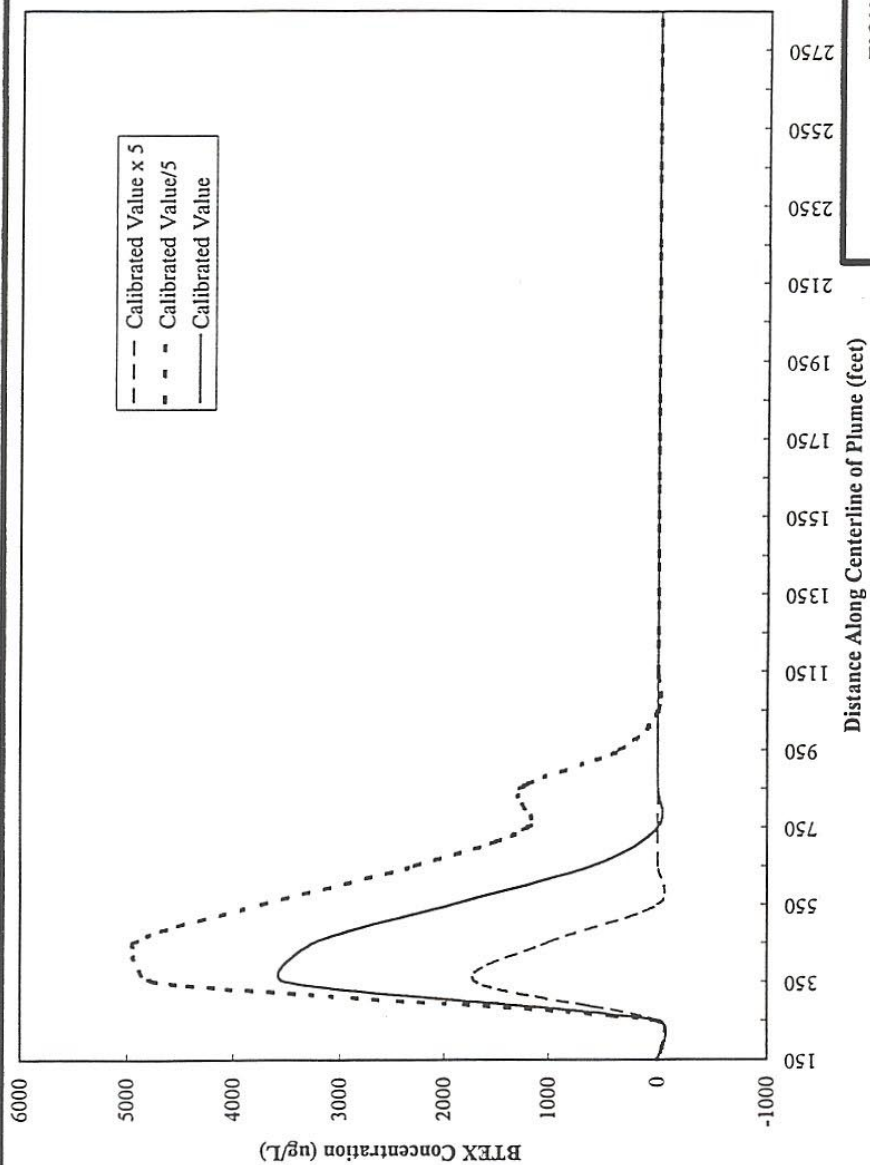


FIGURE 5.7
MODEL SENSITIVITY TO
VARIATIONS IN THE
REACTION COEFFICIENT

Site ST-29
 Intrinsic Remediation TS
 Patrick Air Force Base, Florida

PARSONS
ENGINEERING SCIENCE, INC.
 Denver, Colorado

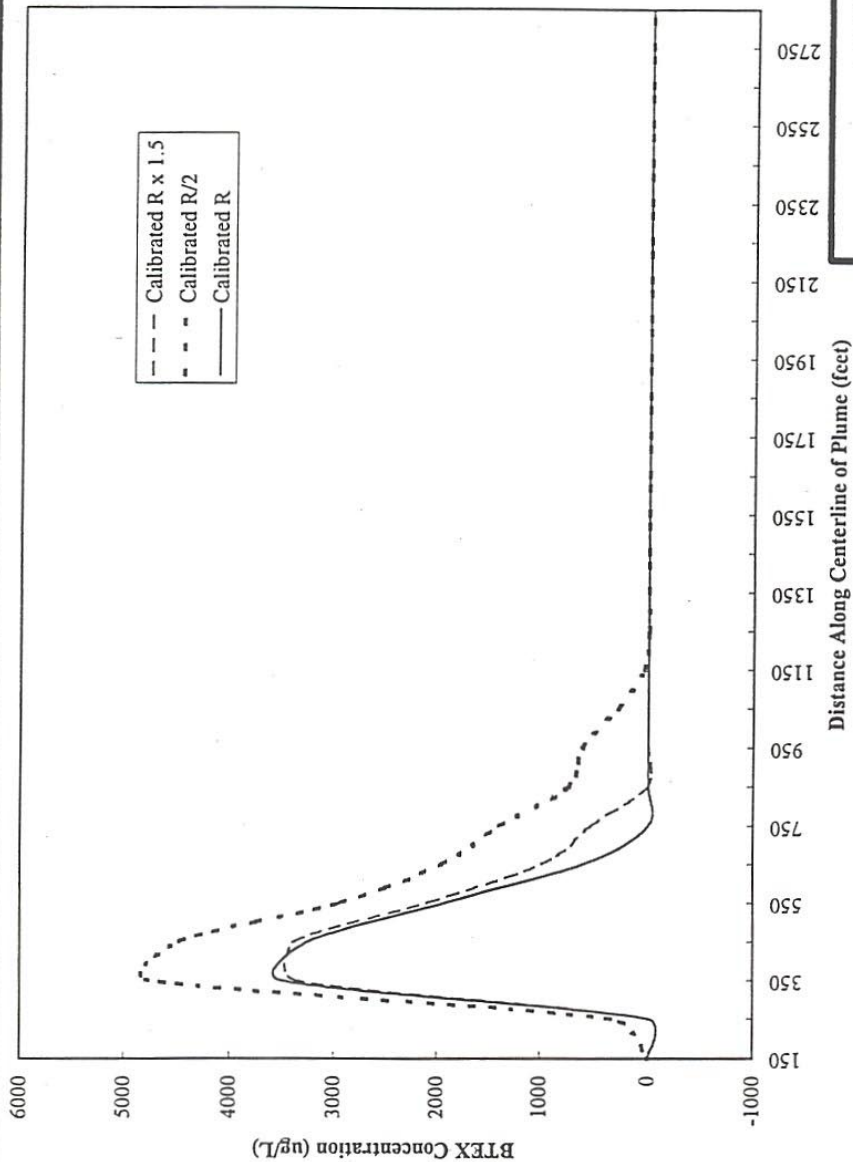


FIGURE 5.8

**MODEL SENSITIVITY TO
VARIATIONS IN THE
COEFFICIENT OF RETARDATION**

Site ST-29
Intrinsic Remediation TS
Patrick Air Force Base, Florida



**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

with the plume. Because more oxygen is present, biodegradation occurs more rapidly. AISO7 the faster groundwater velocity produced by the higher transmissivity initially results in greater spreading of the plume, further exposing the BTEX to oxygenated water. In contrast, decreasing the hydraulic conductivity by a factor of five slowed overall plume migration, which in turn caused an increase in measured BTEX concentrations in the source area and downgradient of the source area. Increased BTEX concentrations in the source area are caused by a reduction in the amount of oxygen being brought into contact with the plume from upgradient locations. This also results in a slightly more elongated plume, because the BTEX can travel farther without being biodegraded.

The effects of varying dispersivity are illustrated by Figure 5.6. Both longitudinal and transverse dispersivity were varied for this analysis, as the ratio of the two values was kept constant at 0.3. Increasing the dispersivity by a factor of five resulted in slightly lower maximum BTEX concentrations and a plume that extended slightly farther downgradient and upgradient from the source area (i.e., the plume was spread out over a greater area). Decreasing dispersivity by a factor of five produced a plume with an extent similar to the calibrated plume, but with higher concentrations.

Figure 5.7 shows the effects of varying the coefficient of reaeration. Increasing this parameter by a factor of five results in a much smaller plume with maximum BTEX concentrations approximately one-half those of the calibrated plume. This is a result of increased oxygen available for biodegradation. Conversely, decreasing the coefficient of reaeration by a factor of five decreases the amount of oxygen available for biodegradation, increasing the length of the plume by 200 feet and increasing the computed maximum BTEX concentrations to approximately 5,000 $\mu\text{g/L}$.

The effects of varying the coefficient of retardation (R) are shown by Figure 5.8. Increasing R by a factor of 1.5 does not have a significant effect on the contaminant distribution. The maximum BTEX concentration is nearly identical, and the plume is approximately 100 feet longer. On the other hand, decreasing R by a factor of two produces a plume that extends almost twice as far downgradient as the original plume and has a higher maximum concentration. These results suggest that the R used for the calibrated simulation is acceptable, as the model is relatively

insensitive to higher values of R, while a value of R that is too low will result in a plume that is much larger than the observed plume.

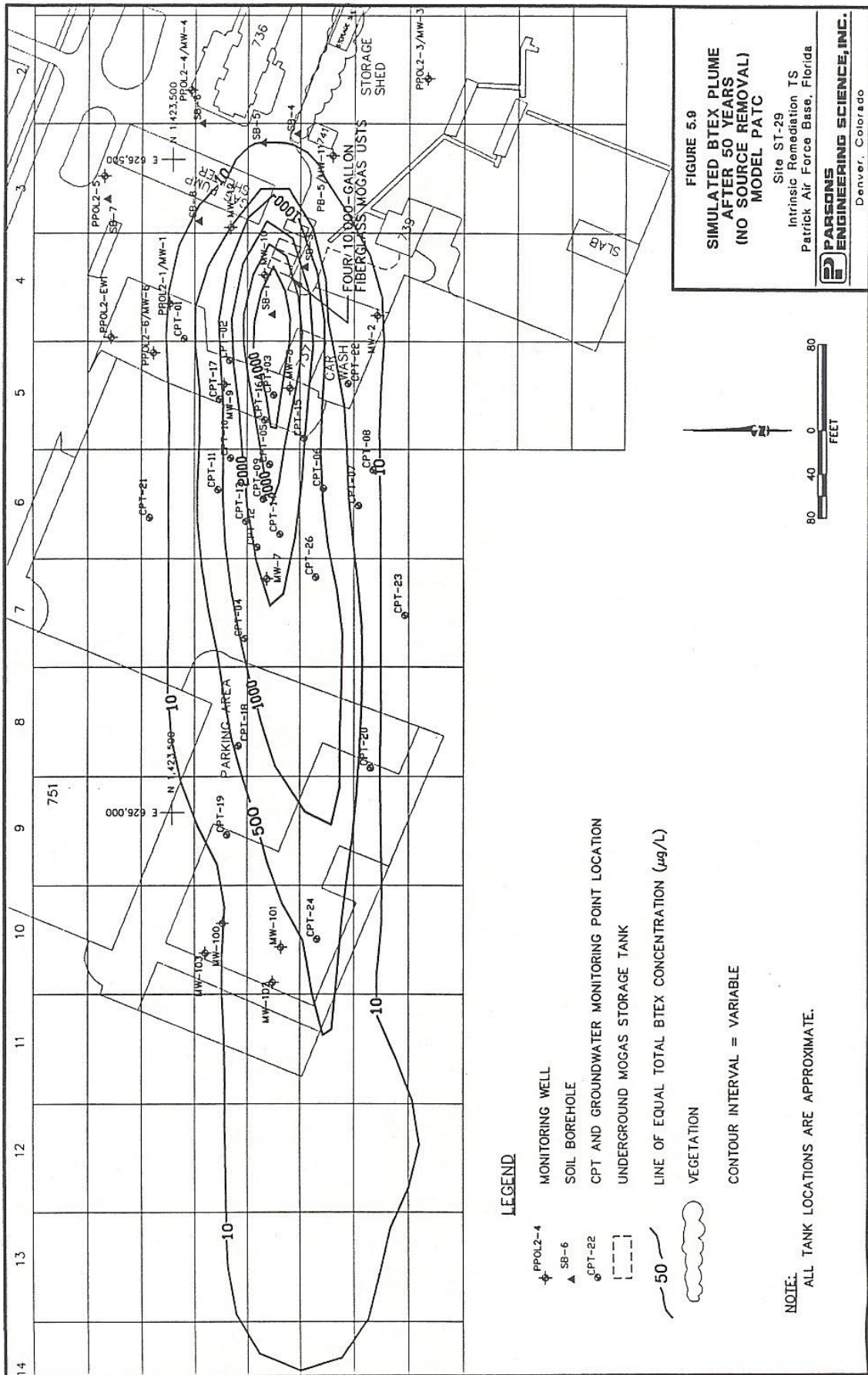
The results of the sensitivity analysis suggest that the calibrated model used for this report is reasonable. The calibrated model is most sensitive to transmissivity and the reaeration coefficient, although the coefficient of retardation is also an important parameter. Increasing the coefficient of reaeration or the transmissivity greatly diminishes the predicted BTEX concentration and distribution. Lowering the values of all three variables lengthens the plume to beyond reasonable distances based on current observations at the site. While the model appears relatively insensitive to dispersivity, adjustment of that parameter contributed significantly toward producing an appropriate plume configuration.

5.6 MODEL RESULTS

To predict fate and transport of dissolved BTEX compounds at Site ST-29, two Bioplume II simulations were run under steady-state conditions. The first simulation assumed no source removal, with contaminant loading continuing at the rates which produced the calibrated model. The second simulation incorporated source reduction over 3 years, ultimately resulting in only 10 percent of the original source loading. This was done to estimate the impact of bioventing, which is currently in use in the source area north of the car wash. Complete input and output files are presented in Appendices C and D. Model results are described in the following sections.

5.6.1 No Source Removal (Model PATC)

Model PATC was used to simulate the migration and biodegradation of the BTEX plume assuming no source reduction or removal. In other words, the loading rates at the injection wells used to produce the calibrated BTEX plume were not reduced by any amount. Contamination therefore was continually introduced at a constant rate. This simulation was run for 50 years beyond the original calibrated model ending time, for a total simulation time of 58 years. Figure 5.9 shows the extent of the main body of the BTEX plume after 50 years of prediction time. Modeled concentrations of less than 10 µg/L were present another 100 feet downgradient of the plume front shown on Figure 5.9. A contour encircling these concentrations was not included because a concentration below 10 µg/L was computed for only one cell.



Throughout this simulation, dissolved BTEX concentrations in the source area increased gradually, with some regular fluctuation of the observed maximum values. This is likely a result of upgradient migration (as a result of dispersion) away from the source area depleting DO concentrations upgradient from the source area, and decreasing the biodegradation capacity of the groundwater entering the source area.

Contaminant migration was relatively slow within the first 10 years of prediction time, with the simulated plume front migrating only about 150 feet beyond the observed plume front. At this time, the BTEX concentration at the plume front was 161 $\mu\text{g/L}$. After 20 years, the computed plume front migrated another 300 feet, with the BTEX concentration at the head of the plume calculated as 35 $\mu\text{g/L}$. Migration was more rapid in the second 10 years of simulation because the plume reached the zone of higher transmissivity defined during calibration for grid rows 14 through 29. After 30 years, the plume extended another 200 feet downgradient, with a total BTEX concentration of 16 $\mu\text{g/L}$ in the cell furthest downgradient. The apparent velocity of the plume has slowed between the 20 and 30-year time step, as the increased distance from the source area results in a more dilute plume front that is more susceptible to biodegradation.

Between 30 and 50 years, the plume appears to stabilize, and the leading edge of the plume does not migrate beyond the extent reached after 30 years of prediction time. The plume front does not remain static in the simulation, cycling between the maximum computed extent and a point 500 feet upgradient. Because the plume front and the maximum concentrations in the source area fluctuate with a regular pattern, there is probably a mathematical instability in the finite difference solution of this problem. However, these results are still useful, indicating that with continuous BTEX loading, the plume is not likely to extend more than 1,200 feet beyond the source area as the plume front disperses and microorganisms are able to degrade hydrocarbons as fast as they are reaching the downgradient extent. In actuality, as the residual hydrocarbons in soil weather and degrade in the source area, the loading rates would decrease, maximum concentrations would decrease, and the dissolved BTEX plume would likely not extend as far downgradient as the model suggests.

5.6.2 Source Removal via Bioventing (Model PATD)

As discussed in Section 1.2, a pilot-scale bioventing system consisting of a 30-foot long horizontal venting well was installed in the area north of the car wash building in March 1993. The location of this system was based on a soil gas survey that indicated that the highest hydrocarbon concentrations were in the area just north of the car wash. In soil gas samples collected during system installation, TVH concentrations in the source area ranged from 38,000 to 100,000 ppmv. Benzene was not detected, while toluene, ethylbenzene, and total xylenes concentrations ranged from 8.3 to 310 ppmv (ES, 1993).

Bioventing is an *in situ* process where low-flow air injection is used to enhance the biodegradation of organic contaminants in subsurface soils by supplying oxygen to indigenous microbes. The pilot-scale system began operating in October 1993, initially as an extraction system due to the high levels of petroleum hydrocarbons. After soil gas concentrations were reduced, the system was switched to air injection in early 1994. As an extraction system, the system extracted hydrocarbon-rich gas from the soil, allowing additional hydrocarbons to volatilize, and drawing in additional oxygen from surrounding soil. The influx of oxygen stimulated microbial degradation of hydrocarbons in the unsaturated zone, and likely increased the oxygen flux across the water table. As an injection system, the bioventing system is injecting air (with approximately 21 percent oxygen) at relatively low flow rates to stimulate additional biodegradation of the fuel residuals. This system increases the flux of oxygen across the water table. For both cases, BTEX compounds are preferentially removed because of their greater solubility and mobility compared to other fuel constituents. In addition, soil near and below the water table will be remediated during times of low water table. Testing during installation of the venting well indicates that the bioventing system is capable of increasing soil gas oxygen concentrations at least 37 feet in all directions from the well.

During initial testing of the bioventing system, results indicated that the system was capable of degrading 900 mg of fuel per kg of soil each year. Soil samples were collected during bioventing system installation, and the total recoverable petroleum hydrocarbon concentrations ranged from 11 to 2,730 mg/kg (ES, 1993). These results suggest that after 3 years, nearly all of the residual fuel in soil within the effective radius of the pilot venting well should be degraded, or equilibrium concentrations should be reached.

Site soil gas data suggest that since the system began operating in October 1993, soil gas hydrocarbon concentrations have decreased significantly. A sample of soil gas from the bioventing well collected in February 1994 contained 1,100 ppmv of TVH. In addition, ethylbenzene and total xylenes were detected at concentrations of 2.3 and 12 ppmv, respectively. Benzene and toluene were not detected at a detection limit of 0.064 ppmv (ES, unpublished data). Comparison of these data to the data collected during system installation indicates a significant decrease in soil gas TVH and BTEX concentrations.

Evaluation of bioventing results at 16 other sites (including sites with conditions similar to those at Site ST-29) shows that after 1 year of operation, average BTEX concentrations in soil were reduced by 91 percent (for benzene) to greater than 99 percent (for ethylbenzene and xylenes) (ES, 1994b). During the same time frame, average soil TPH concentrations were reduced by 70 percent, confirming that the BTEX compounds are preferentially removed.

Given the record of bioventing performance and the site-specific soil gas sampling results, it appears that soil BTEX concentrations have been significantly reduced and will continue to be reduced while the pilot-scale bioventing system is in operation. Installation of a full-scale bioventing system (scheduled for 1995) will further reduce the mass of hydrocarbons in the entire contaminated vadose zone soil volume. Based on this information, another predictive model was set up to reflect source removal. As a starting assumption, this model (PATD) assumed that in 1 year of bioventing system operation, 50 percent of the soil BTEX was removed. In the second year of operation, the model set-up assumed that an additional 25 percent of the BTEX was removed. In the third and all subsequent years of operation, it was assumed that steady-state conditions were reached, with 10 percent of the BTEX remaining.

To simulate the reduction in BTEX concentrations, it was assumed that reductions in soil concentrations produced similar reductions in the BTEX loading rates. For example, for the first predictive year of the PATD simulation (year 9 of the total simulation), the loading rates at each injection well were reduced to 50 percent of the calibrated model rates. In the second predictive year the loading rates were decreased to 25 percent of the original rates, and in the third and all subsequent years the loading rates were left at 10 percent of the original rates. While the absence of confirmatory soil samples makes it difficult to quantify the actual decrease in loading rates that will be brought about by bioventing, the model based on this assumption can provide an indication

of the potential effects of source reduction. Confirmatory soil sampling will take place in the bioventing pilot test area in December 1994.

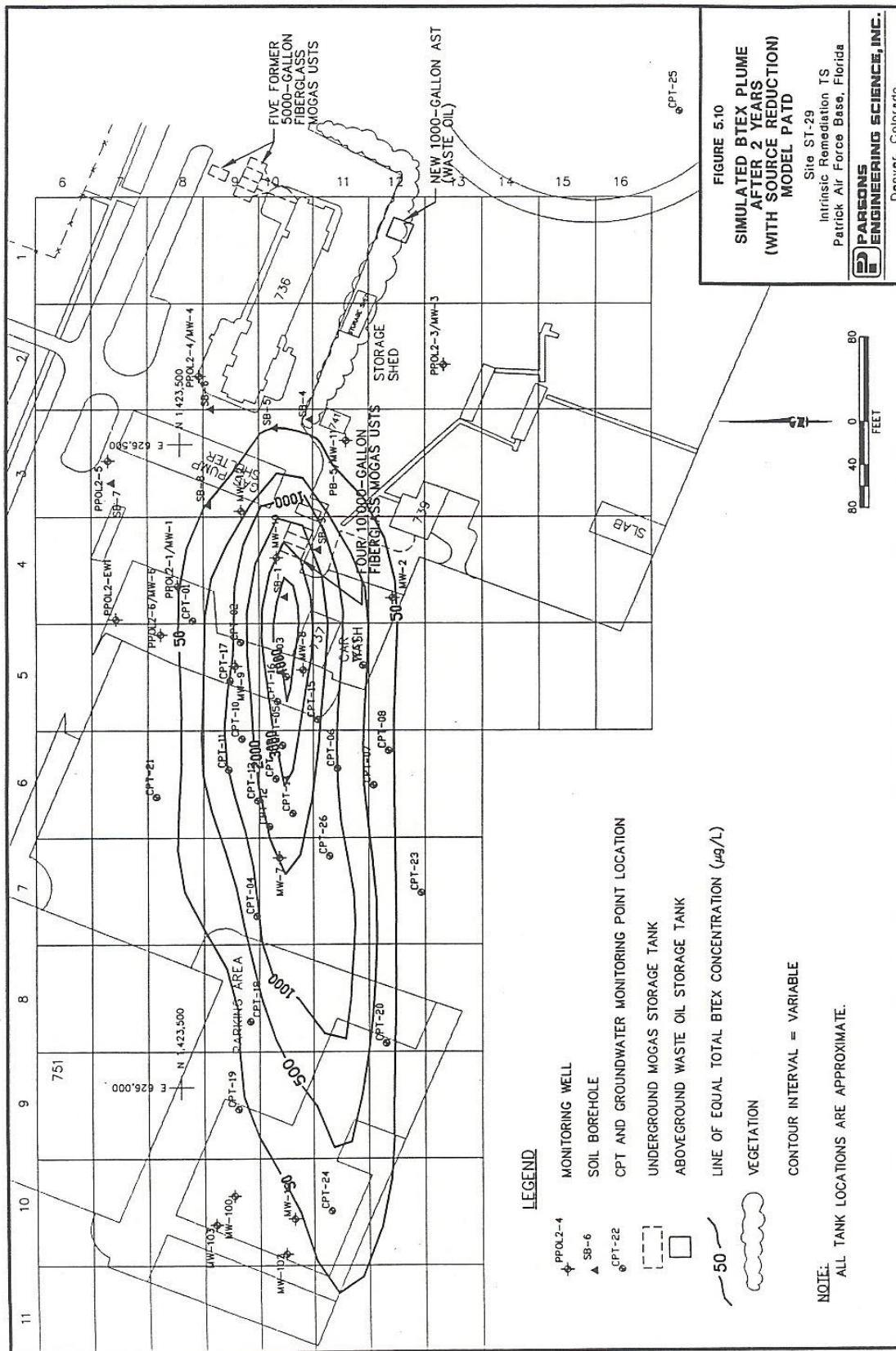
Model results for this case suggest that within 7 years after source reduction began, the dissolved BTEX compounds will not be present in groundwater at the site. Reduction of the source results in rapid biodegradation of the remaining concentrations of hydrocarbons, because the lower loading rates do not introduce BTEX into the aquifer at a rate that outpaces the rate of biodegradation and the rate of sorption onto the aquifer matrix. Figures 5.10, 5.11, and 5.12 show the results of this model after 2, 3, and 5 years of source reduction, respectively.

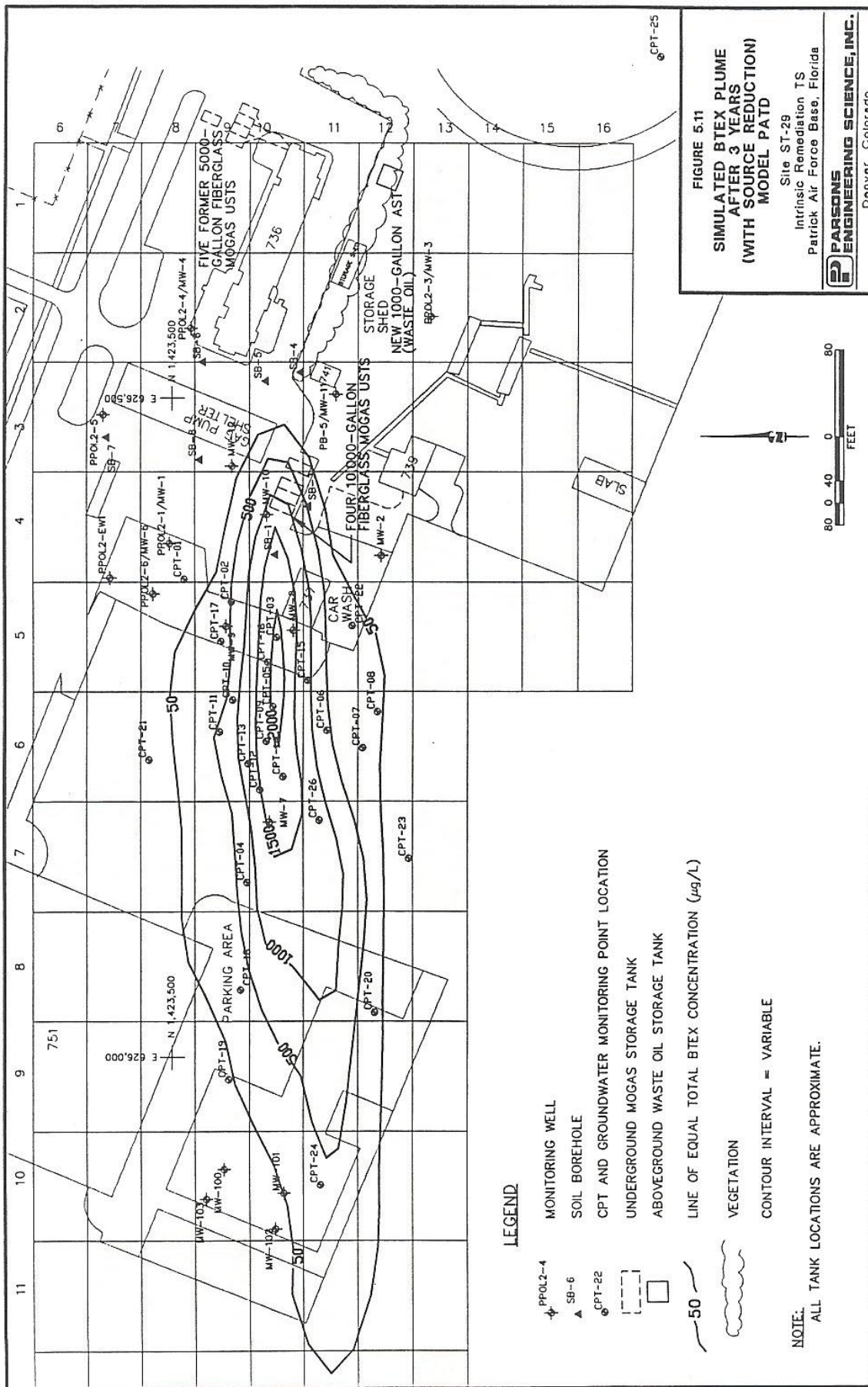
After 2 years (Figure 5.10), the plume has not migrated beyond the observed extent, while the maximum calculated concentration in the source area actually increases to 4,253 µg/L. After 3 years (Figure 5.11) the plume front was only about 100 feet beyond the observed limit, and the maximum calculated concentration decreases to 948 µg/L. Five years after source reduction is initiated, the model predicts that the plume front retreats to the approximate extent of the observed plume (Figure 5.12), and the maximum calculated concentration decreases to 326 µg/L. Seven years after source reduction began, the dissolved BTEX plume is completely degraded.

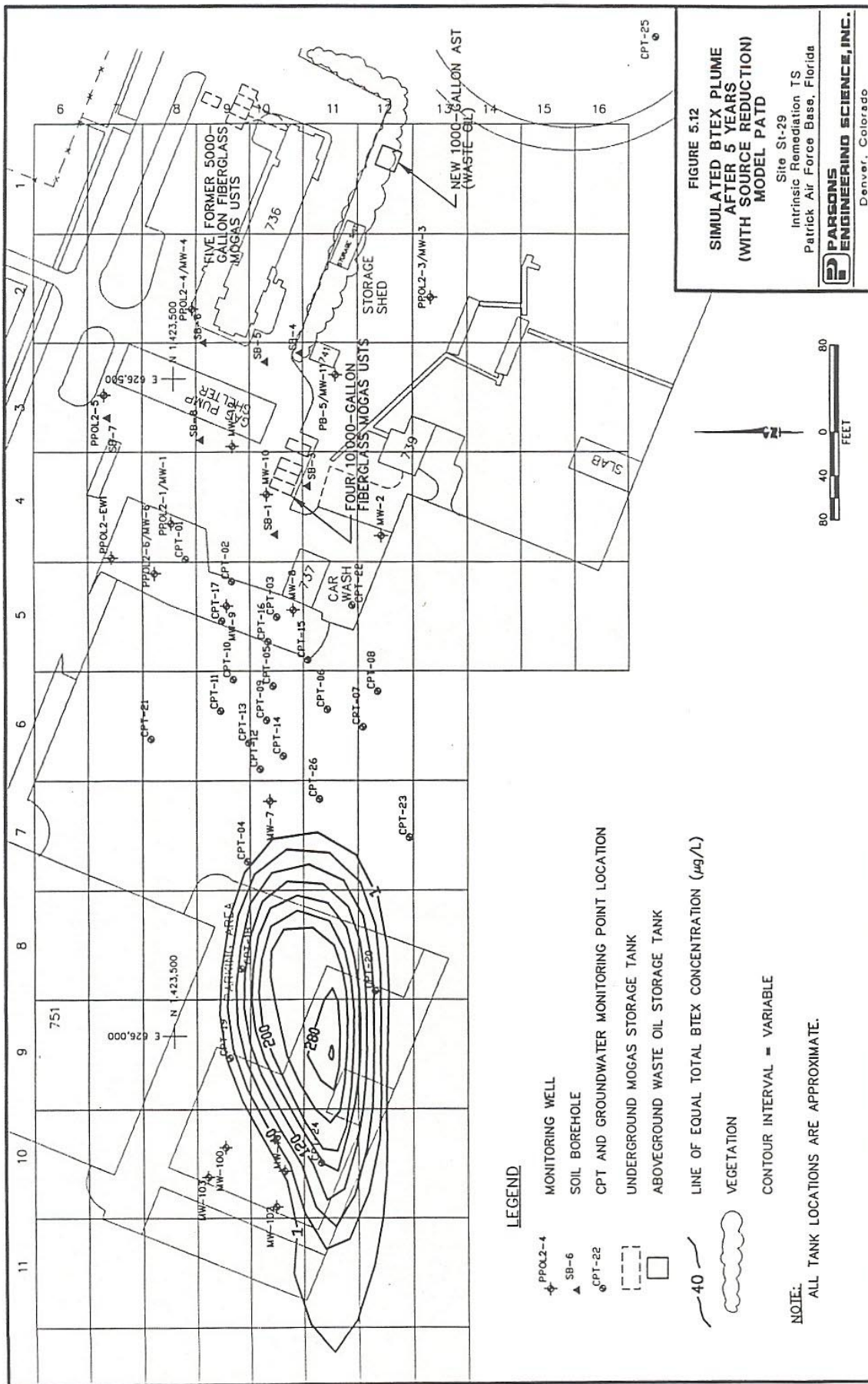
5.7 CONCLUSIONS AND DISCUSSION

The results of two different Bioplume II model scenarios at the BX Service Station indicate that dissolved BTEX contamination is not likely to migrate more than 1,200 feet downgradient from the source area. The first scenario, model PATC, assumed that BTEX loading rates in the source area would remain constant (at the rates used to calibrate the BTEX plume) for the full duration of the simulation. The second scenario, model PATD, assumed that BTEX loading rates would be reduced via bioventing in the source area. PATC results suggest that after 30 years, the BTEX plume will reach its maximum extent, approximately 1,200 feet downgradient from the source area. PATD results suggest that after source reduction, BTEX compounds will migrate no more than 600 feet downgradient from the source area and will be degraded within 7 years.

Model results imply that as a worst-case scenario, BTEX compounds would migrate approximately 1,200 feet downgradient from the source area, or no more than 800 feet beyond the observed extent of the plume indicated by the March 1994 sampling results. Taking into account the model cell size and the resolution of concentrations at the margin







of the plume, it appears unlikely that detectable concentrations of BTEX will reach the Banana River or any other potential receptors more than 1,400 feet downgradient from the site.

In both cases, model simulations are very conservative for several reasons, including:

- 1) Aerobic respiration, iron reduction, and methanogenesis are all occurring at this site; however, only DO was considered as an electron acceptor during model simulations;
- 2) The stoichiometry used to determine the ratio between DO and total BTEX assumed that no microbial cell mass was produced during the reaction. As discussed in Section 4.3.3.1, this approach may be too conservative by a factor of three.
- 3) The highest DO concentration observed at the site was 3.7 mg/L (CPR-25). The highest DO concentration assumed during model simulations was 3.5 mg/L.
- 4) A mid-range coefficient of retardation for benzene (2.7) was used for model simulations. Coefficient of retardation values for the other BTEX compounds range from 1.3 to 17.7. The use of the low coefficient of retardation tends to increase the distance traveled by the simulated BTEX plume, but provides a more accurate estimate of benzene transport.

Source reduction through bioventing, in concert with natural attenuation, can greatly impact the persistence of the BTEX contamination observed at the site. Comparing the results of the PATC model with the results of the PATD simulation shows the effects of source reduction, which allows for more rapid and thorough degradation of the BTEX compounds. The rapid degradation of BTEX observed in simulation PATD is feasible, given the observed DO concentrations, the maximum observed BTEX concentrations, and the conservative assumptions made in constructing the simulation. Bioventing is already in operation, and appears to have significantly reduced residual soil BTEX concentrations. Geochemical evidence also strongly suggests that anaerobic biodegradation is occurring in the central portions of the plume, which would further increase the rates of hydrocarbon consumption. Further, the high groundwater temperatures observed at this site are likely

to promote rapid reproduction of microorganisms, which would also result in more rapid degradation of hydrocarbons.

Models PATC and PATD represent two endpoints in a continuum of probable scenarios at Site ST-29. PATC represents the "worst case" in that it assumes BTEX dissolution into the aquifer will continue at the same rate indefinitely, while BTEX loading rates should actually decrease as the residual product weathers and the continuing dissolution removes more and more of those compounds. Model PATD is a more realistic prediction that assumes removal of BTEX from the soil via bioventing will result in a proportional decrease in BTEX partitioning into the aqueous phase. It is likely that future site conditions will fall somewhere between these endpoints, with the plume not extending as far as indicated by PATC, but with BTEX in the source area persisting longer than predicted by PATD.

SECTION 6

COMPARATIVE ANALYSIS OF REMEDIAL ALTERNATIVES

This section presents the development and comparative analysis of two groundwater remedial alternatives for Site ST-29, the BX Service Station, at Patrick AFB. The intent of this evaluation is to determine if intrinsic remediation is an appropriate and cost-effective remedial approach to consider when developing final remedial strategies for Site ST-29, especially when combined with other innovative and conventional remedial technologies.

Section 6.1 presents the evaluation criteria used to evaluate groundwater remedial alternatives. Section 6.2 discusses the development of remedial alternatives considered part of this demonstration project. Section 6.3 provides a brief description of each of these remedial alternatives. Section 6.4 provides a more detailed analysis of the remedial alternatives using the defined remedial alternative evaluation criteria. The results of this evaluation process are summarized in Section 6.5.

6.1 REMEDIAL ALTERNATIVE EVALUATION CRITERIA

The evaluation criteria used to identify the appropriate remedial alternative for shallow groundwater contamination at Site ST-29 were adapted from those recommended by the USEPA for selecting remedies for Superfund sites [Office of Solid Waste and Emergency Response (OSWER) Directive 9902.3]. These criteria included (1) long-term effectiveness and permanence, (2) technical and administrative implementability, and (3) relative cost. The following sections briefly describe the scope and purpose of each evaluation criterion. This report does not include a complete discussion of all potentially applicable regulatory objectives for the site. Rather, this report focuses on the potential use of intrinsic remediation and source reduction technologies to reduce BTEX concentrations within the shallow groundwater to regulatory concentrations intended to be protective of human health and the environment.

6.1.1 Long-Term Effectiveness and Permanence

Each remedial approach or remedial alternative (which can be a combination of remedial approaches such as intrinsic remediation and institutional controls) was analyzed to determine how effectively it will minimize groundwater plume expansion so that groundwater quality standards or target cleanup goals can be achieved at a downgradient point of compliance (POC). The expected technical effectiveness based on case histories from other sites with similar conditions also is evaluated. The ability to minimize potential impacts to surrounding facilities and operations is considered. Also, the ability of each remedial alternative to protect both current and potential future receptors from potential risks associated with site-related contamination in shallow groundwater is qualitatively assessed by conservatively estimating if a potential exposure pathway involving groundwater could be completed, either now or in the future. This evaluation criterion also included permanence and the ability to reduce contaminant mass, toxicity, and volume. Time to implementation and time until protection is achieved are described. Long-term reliability for providing continued protection, including an assessment of potential for failure of the technology and the potential threats resulting from such a failure, also is evaluated.

6.1.2 Implementability

The technical implementation of each remedial technology or remedial alternative was evaluated in terms of technical feasibility and availability. Potential shortcomings and difficulties in construction, operations, and monitoring are presented and weighed against perceived benefits. Requirements for any post-implementation site controls such as LTM and land or groundwater use restrictions are described. Details on administrative feasibility in terms of the likelihood of public acceptance and the ability to obtain necessary approvals are discussed.

6.1.3 Cost

The total cost (present worth) of each remedial alternative was estimated for relative comparison. An estimate of capital costs, and operations and post-implementation costs for site monitoring and controls is included. An annual inflation factor of 5 percent was assumed in discounted present worth calculations.

6.2 FACTORS INFLUENCING ALTERNATIVES DEVELOPMENT

Several factors were considered during the identification and screening of remedial technologies for addressing shallow groundwater contamination at Site ST-29. Factors considered included the objectives of the natural attenuation demonstration program; contaminant, groundwater, and soil properties; present and future land use; and potential receptors and exposure pathways. The following section briefly describes each of these factors and how they were used to narrow the list of potentially applicable remedial technologies to the final remedial alternatives considered for Site ST-29.

6.2.1 Program Objectives

The intent of the Natural Attenuation (Intrinsic Remediation) Demonstration Program sponsored by AFCEE is to develop a systematic process for scientifically investigating and documenting naturally occurring subsurface attenuation processes that can be factored into overall site remediation plans. The objective of this program and the specific Site ST-29 study is to provide solid evidence of intrinsic remediation of dissolved fuel hydrocarbon so that this information can be used by the Base and its prime environmental contractor(s) to develop an effective groundwater remediation strategy. A secondary goal of this multi-site initiative is to provide a series of regional case studies that demonstrate that natural processes of contaminant degradation can often reduce contaminant concentrations in groundwater to below acceptable cleanup standards before completion of potential exposure pathways.

Because the objective of this program is to study natural processes in the saturated zone rather than all contaminated media (soil, soil gas, etc.), technologies have been evaluated based on their potential impact on shallow groundwater and phreatic soils. Technologies that can reduce vadose zone contamination and partitioning of contaminants into groundwater have also been evaluated. Many of the source removal technologies evaluated in this section will reduce soil and soil gas contamination, but it is important to emphasize that the remedial alternatives developed in this document are not intended to remediate all contaminated media. Additional program objectives set forth by AFCEE include cost effectiveness and minimization of waste. Technologies that may meet these criteria include institutional controls, soil vapor extraction, bioventing, biosparging, groundwater pump and treat, and intrinsic remediation. Soil excavation, slurry walls, sheet piling, carbon adsorption, *ex situ* biological or chemical treatment, and onsite/offsite disposal are not attractive technology candidates for this site.

6.2.2 Contaminant Properties

The site-related contaminants considered as part of this demonstration at Site ST-29 are the BTEX compounds. The source of this contamination is weathered MOGAS present as residual contamination in capillary fringe and saturated soil within the source area of Site ST-29. The physiochemical characteristics of both MOGAS and the individual BTEX compounds will greatly influence the effectiveness and selection of a remedial technology.

Petroleum hydrocarbon mixtures, such as MOGAS, are comprised of over 300 compounds with different physiochemical characteristics. MOGAS is classified as an LNAPL with a liquid density of 0.68 to 0.76 gram per cubic centimeter (g/cc) at 20°C. Many compounds within MOGAS sorb very well to soil and are concentrated in the capillary fringe because the mixture is less dense than water. MOGAS is slightly soluble in water, with a maximum solubility of approximately 200 mg/L. MOGAS is also a primary substrate for biological metabolism. Simultaneous biodegradation of aliphatic, aromatic, and alicyclic hydrocarbons has been observed. In fact, mineralization rates of hydrocarbons in mixtures, such as MOGAS or JP-4, may be faster than mineralization of the individual constituents as a result of cometabolic pathways (Jamison *et al.*, 1975; Perry, 1984).

The BTEX compounds are generally volatile, highly soluble in water, and adsorb less strongly to soil than other hydrocarbons in a petroleum mixture. These characteristics allow the BTEX compounds to leach more rapidly from contaminated soil into groundwater and migrate as aqueous-phase contamination (Lyman *et al.*, 1992). All of the BTEX compounds are highly amenable to *in situ* degradation by both biotic and abiotic mechanisms.

Benzene is very volatile with a vapor pressure of 76 millimeters of mercury (mm Hg) at 20°C and a Henry's Law Constant of approximately 0.0054 atmosphere-cubic meters per mole (atm-m³/mol) at 25°C (Hine and Mookerjee, 1975; Jury *et al.*, 1984). The solubility of pure benzene in water at 20°C has been reported to be 1,780 mg/L (Verschueren, 1983). Benzene is normally biodegraded to carbon dioxide, with catechol as a short-lived intermediate (Hopper, 1978; Ribbons and Eaton, 1992).

Toluene is also volatile, with a vapor pressure of 22 mm Hg at 20°C and a Henry's Law Constant of about 0.0067 atm-m³/mol at 25°C (Pankow and Rosen, 1988; Hine and Mookerjee, 1975). Toluene sorbs more readily to soil media relative to benzene, but still is very mobile. The solubility of pure toluene in water at 20°C is approximately 515 mg/L at 20°C (Verschueren, 1983). Toluene has been shown to degrade to pyruvate, caetaldehyde, and completely to carbon

dioxide via the intermediate catechol (Hopper, 1978; Wilson *et al.*, 1986; Ribbons and Eaton, 1992).

Ethylbenzene has a vapor pressure of 7 mm Hg at 20°C and a Henry's Law Constant of 0.0066 atm-m³/mol (Pankow and Rosen, 1988; Valsaraj, 1988). Ethylbenzene sorbs more strongly to soils than benzene but less strongly than toluene (Abdul *et al.*, 1987). Pure ethylbenzene is also less soluble than benzene and toluene in water at 152 mg/L at 20°C (Verschueren, 1983; Miller *et al.*, 1985). Ethylbenzene ultimately degrades to carbon dioxide via its intermediate 3ethylcatechol (Hopper, 1978; Ribbons and Eaton, 1992).

The three isomers of xylene have vapor pressures ranging from 7 to 9 mm Hg at 20°C and Henry's Law Constants of between 0.005 and 0.007 atm-m³/mol at 25°C (Mackay and Wolkoff, 1973; Hine and Mookerjee, 1975; Pankow and Rosen, 1988). Of all of the BTEX compounds, xylenes sorb most strongly to soil, but still can leach from soil into the groundwater (Abdul *et al.*, 1987). Pure xylenes have water solubilities of 152 to 160 mg/L at 20°C (Bohon and Claussen, 1951; Mackay and Shiu, 1981; Isnard and Lambert, 1988). Xylenes can degrade to carbon dioxide via pyruvate carbonyl intermediates (Hopper, 1978; Ribbons and Eaton, 1992).

Based on these physiochemical characteristics, intrinsic remediation, soil vapor extraction, bioventing, biosparging, groundwater extraction, and air stripping technologies could all be effective at collecting, destroying, and treating BTEX contaminants at Site ST-29.

6.2.3 Site-Specific Conditions

Two general categories of site-specific characteristics were considered when identifying remedial technologies for comparative evaluation as part of this demonstration project. The first category was physical characteristics such as groundwater depth, gradient, flow direction, and soil type, which influence the types of remedial technologies most appropriate for the site. The second category involved assumptions about future land use and potential receptors and exposure pathways. Each of these site-specific characteristics have influenced the selection of remedial alternatives included in the comparative evaluation.

6.2.3.1 Groundwater and Soil Characteristics

Site geology and hydrogeology will have a profound effect on the transport of contaminants and the effectiveness and scope of required remedial technologies at a given site. Hydraulic conductivity is perhaps the most important aquifer parameter governing groundwater flow and

contaminant transport in the subsurface. The velocity of the groundwater and aqueous-phase contamination is directly related to the hydraulic conductivity of the saturated zone. Rising head slug tests completed at Site ST-29 indicate a relatively high conductivity within the vicinity of the source area and dissolved BTEX plume. Estimated values ranged from 9.6×10 to 8.9×10 ft/min. These high values are characteristic of sandy materials (see Sections 4 and 5 of this report). The high hydraulic conductivity at this site directly influences the fate and transport of contaminants. The shallow groundwater plume has migrated relatively rapidly, increasing the extent of contamination (i.e., the plume has expanded) but decreasing the average concentration within the aquifer through dilution and increased biodegradation.

Although high hydraulic conductivity can result in plume expansion and migration, this same characteristic also will enhance the effectiveness of other remedial technologies, such as groundwater-extraction, biosparging, and intrinsic remediation. For example, it should be less expensive and time-consuming to capture and treat the contaminant plume using a network of extraction wells in areas of high hydraulic conductivity. Contaminant recovery also may be maximized when contaminants are not significantly sorbed to and retarded by phreatic soil. However, the relatively high TOC content of Patrick AFB aquifer materials (0.016 to 1.86 percent) will tend to enhance sorption and decrease the mobility of all BTEX compounds. The effectiveness of biosparging also may be increased in highly conductive aquifers because of reduced entry pressures and increased radius of influence. Greater hydraulic conductivity also increases the amount of contaminant mass traveling through the biosparging network. The DO introduced through biosparging can also enhance aerobic degradation of the dissolved contaminant mass.

The rapid movement of contaminants within the subsurface away from the source also will increase the effectiveness of natural biodegradation processes by distributing the contaminant mass into areas enriched with electron acceptors. To satisfy the requirements of indigenous microbial activity and intrinsic remediation, the aquifer also must provide an adequate and available carbon or energy source, electron acceptors, essential nutrients, proper ranges of pH, temperature, and redox potential.

Data collected as part of the field work phase of this demonstration project and described in Sections 3 and 4 of this document indicate that Site ST-29 is characterized by adequate and available carbon/energy sources and electron acceptors to support measurable biodegradation of MOGAS contamination by indigenous microorganisms. Both DO and carbon dioxide (which is

utilized during methanogenesis) represent significant sources of electron acceptor capacity for the biodegradation of BTEX compounds at the site. Further, because fuel hydrocarbon-degrading microorganisms have been known to thrive under a wide range of temperature and pH conditions (Freeze and Cherry, 1979), the physical and chemical conditions of the groundwater and phreatic soil at Site ST-29 are not likely to inhibit microorganism growth.

Fuel hydrocarbon-degrading microorganisms are ubiquitous and as many as 28 hydrocarbon-degrading isolates (bacteria and fungi) have been discovered in different soil environments (Davies and Westlake, 1977; Jones and Eddington, 1968). Indigenous microorganisms have a distinct advantage over microorganisms injected into the subsurface to enhance biodegradation because indigenous microorganisms are well adapted to the physical and chemical conditions of the subsurface in which they reside (Goldstein *et al.*, 1985). Microbe addition was not considered a viable remedial technology for Site ST-29.

6.2.3.2 Potential Exposure Pathways

An exposure assessment identifies the potential human and ecological receptors that could potentially come into contact with site-related contamination and the pathways through which these receptors might be exposed. To have a completed exposure pathway, there must be a source of contamination, a potential mechanism(s) of release, a pathway of transport to an exposure point, an exposure point, and a receptor. If any of these elements do not exist, the exposure pathway is considered incomplete, and receptors will not come into contact with site related contamination. Evaluation of the potential long-term effectiveness of any remedial technology or remedial alternative as part of this demonstration project includes determining if the approach will be sufficient and adequate to minimize plume expansion so that potential exposure pathways involving shallow groundwater are incomplete.

Assumptions about current and future land use at a site form the basis for identifying potential receptors, potential exposure pathways, reasonable exposure scenarios, and appropriate remediation goals. USEPA (1991) advises that the land use associated with the highest (most conservative) potential level of exposure and risk that can reasonably be expected to occur should be used to guide the identification of potential exposure pathways and to determine the level to which the site must be remediated. The source area consists of fuel storage and retail facilities associated with the BX Service Station. Warehouses/hangars, runway infields, and the Base sewage disposal plant are located to the west of Site ST-29. The area south and east of the site is

occupied by aircraft runways and their associated infields. The groundwater plume originating from Site ST-29 is migrating to the west, and has impacted shallow groundwater in an area extending from the source area to an area just south of Building 751. The current land use within and downgradient from the contaminant plume is entirely industrial. The Banana River is located approximately 2,600 to 2,800 feet downgradient from the site.

Under reasonable current land use assumptions, potential human receptors only include worker populations. It is unlikely that workers could be exposed to site-related contamination in phreatic soils or shallow groundwater unless this material was removed during future construction excavations or remedial activities. Utility workers could be exposed to shallow groundwater contamination if the plume impacts the storm drain located just west of the car wash. Shallow groundwater is not currently used to meet any demands at Patrick AFB. All on-Base water demands are met by deep supply wells and/or from water piped in from the City of Cocoa. Exposure pathways involving other environmental media such as shallow soils and soil gas in the source area were not considered as part of this project, but should be considered in overall site remediation decisions.

Ecological receptors typically include nondomestic plants and animals that could be exposed to affected site media. Unless groundwater discharges at the ground surface or into a surface water body, the only ecological receptors potentially exposed to contaminated groundwater are plants with root zones extending to the water table, and possibly burrowing animals. At Site ST-29, groundwater occurs at 4 to 5 feet bgs, which is conceivably within the root zone of some plants. However, the industrial setting of the site and the fact that the portion of the Base downgradient from Site ST-29 toward which the BTEX plume is migrating is entirely covered by concrete (Figure 1.1), seriously limits the types of potential vegetation or animal receptors present. Moreover, little information is available in the toxicological literature to suggest that exposure of plants or terrestrial animals to organic compounds such as BTEX poses a significant hazard (Micromedex, Inc., 1995).

No surface expression of groundwater has been observed at the BX Service Station; groundwater is expected to discharge to the Banana River, some 2,800 feet downgradient from the site. Migration to and discharge of contaminated groundwater into the Banana River could complete an exposure pathway to human or ecological receptors via dermal contact or possible ingestion, but it is very unlikely that detectable concentrations could reach the river. In addition,

any contaminants reaching the river from Site ST-29 would likely be instantly diluted to nondetectable concentrations.

Assumptions about hypothetical future land uses must also be made to ensure that the remedial technology or alternative considered for shallow groundwater at the site is adequate and sufficient to provide long-term protection. No changes in land use are anticipated in the foreseeable future, so use of an industrial land use assumption is the most appropriate. Thus, potential human future receptors include only worker populations. Special-concern ecological receptors are not likely to be exposed to adverse concentrations of BTEX in groundwater. The potential future exposure pathways involving workers are identical to those under current conditions provided shallow groundwater is not used to meet industrial water demands. In summary, the use of the intrinsic remediation technology at this site will require that the source area be maintained as industrial property and that restrictions on groundwater use be enforced in areas downgradient of Site ST29 to the Banana River. If source removal technologies such as soil vapor extraction, bioventing, free product recovery, biosparging or groundwater pump and treat are implemented, they will have some impact on the short- and long-term land use options and will require some level of institutional control and worker protection during remediation.

6.2.3.3 Remediation Goals for Shallow Groundwater

Worst-case model results suggest that BTEX compounds are not likely to migrate more than 1,200 feet downgradient from the source area, assuming no additional contaminants (i.e., NAPLs) are discharged to the subsurface. As source-area remediation proceeds via bioventing, and as residual LNAPL weathers, BTEX loading rates will decrease, and the extent of BTEX migration will likely be much more limited. Therefore, an area approximately 1,000 feet beyond the plume boundary observed in March 1994 has been identified as the POC for groundwater remedial activities because this appears to be the maximum extent of future contaminant migration. This is a suitable location for monitoring and for demonstrating compliance with protective groundwater quality standards, such as promulgated FAC groundwater cleanup levels or drinking water MCLs.

This remedial strategy assumes that compliance with promulgated, single-point remediation goals is not necessary if site-related contamination does not pose a threat to human health or the environment (i.e., exposure pathways are incomplete). Thus, the magnitude of required remediation in areas that can and will be placed under institutional control is different from the

remediation that is required in areas that may be available for unrestricted use. The primary RAO for shallow groundwater within and downgradient of Site ST-29 is limited plume expansion to prevent exposure of downgradient receptors to concentrations of BTEX in groundwater, or Banana River surface water, at concentrations that exceed protective regulatory levels. This means that viable remedial alternatives must be able to achieve concentrations that minimize plume migration and/or expansion. The RAO for shallow groundwater at the POC is attainment of the state target cleanup levels for Class G-II groundwater for each of the compounds listed in Table 6.1. Although it is unlikely that groundwater would be ingested by humans, this level of long-term protection is appropriate, because the shallow groundwater in this area is classed by FDER as G-II (potable). Moreover, attainment of the BTEX and VOC cleanup levels listed in Table 6.1 would ensure that state surface water criteria for the protection of aquatic organisms in the Banana River, all of which are equal to or greater than the groundwater levels listed in Table 6.1 (Chapter 62-302, FAC), also would be attained should the site contaminants reach the river.

In summary, available data suggest that there is no completed potential exposure pathway involving shallow groundwater under current conditions. It is likely that no potential exposure pathways involving shallow groundwater would be complete under future land use assumptions, provided use of groundwater as a potable or industrial source of water is prohibited by institutional controls within the source area and within an area approximately 1,400 feet downgradient of the source area, and provided the Banana River is not impacted. Thus, institutional controls are likely to be a necessary component of any groundwater remediation strategy for this site. The required duration of these institutional controls may vary depending on the effectiveness of the selected remedial technology at reducing contaminant mass and concentration in the groundwater.

TABLE 6.1
POINT-OF-COMPLIANCE REMEDIATION GOALS
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

Compound	Groundwater Target Level (µg/L) ^{a/}
Benzene	1
Total Volatile Organic Aromatics	50
1,2-Dichloroethane	3
1,2-Dibromoethane	0.02
Lead	50
Methyl tert-butyl ether	50

6.2.4 Summary of Remedial Technology Screening

Several remedial technologies have been identified and screened for use in treating the shallow groundwater at Site ST-29. Table 6.2 identifies the initial remedial technologies considered as part of this demonstration and those retained for detailed comparative analysis. Screening was conducted systematically by considering the program objectives of the AFCEE intrinsic remediation demonstration, applicable state cleanup goals, physiochemical properties of the BTEX compounds, and other site-specific characteristics such as hydrogeology, land use assumptions, potential exposure pathways, and other appropriate remediation goals. All of these factors will influence the technical effectiveness, implementation, and relative cost of technologies for remediating shallow groundwater underlying and migrating from the site. The remedial approaches and technologies retained for development of remedial alternatives and comparative analysis include institutional controls, intrinsic remediation, LTM, bioventing/soil vapor extraction, and biosparging.

6.3 BRIEF DESCRIPTION OF REMEDIAL ALTERNATIVES

This section describes how remedial technologies/approaches retained from the screening process were combined into two remedial alternatives for Site ST-29. Sufficient information on each remedial alternative has been provided to facilitate a comparative analysis of effectiveness, implementability, and cost in Section 6.4.

6.3.1 Alternative 1 - Bioventing in Source Area, Intrinsic Remediation, and Institutional Controls with Long-Term Monitoring

Pilot-scale bioventing is underway in the source area at site ST-29. A single, horizontal-well bioventing system is currently injecting air into the subsurface and providing oxygen to approximately 1,000 to 1,200 cubic yards of the most contaminated unsaturated soils. In 1995, the existing bioventing system will be expanded by the installation of additional vent wells in the source area. Under this alternative, bioventing activities would continue (with the expanded system), but no additional source removal technologies would be employed. As indicated in Section 5.7.2, it has been estimated that this system will result in removal of 90 percent of the residual soil BTEX compounds within 3 years with an assumed proportional decrease in BTEX dissolution into shallow groundwater. Bioventing is preferred over soil vapor extraction because bioventing uses low rates of air injection that do not create vapor emissions into the atmosphere.

TABLE 6.2
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF
TECHNOLOGIES AND PROCESS OPTIONS FOR GROUND WATER REMEDIATION
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

General Response Action	Technology Type	Process Option	Implementability	Retain
Long-Term Monitoring	Periodic Ground Water Monitoring	Confirmation Wells	Many existing wells are available to confirm the progress of remediation.	Yes
		Point-of-Compliance Wells	Sufficient distance exists between the plume and point-of-compliance to locate several wells.	Yes
Institutional Controls	Ground Water Use Control	Land Use Control/Regulate Well Permits	Plume area is currently within the base boundary and land-use and ground water use are under base jurisdiction.	Yes
		Seal/Abandon Existing Wells	No production wells are known to exist in the existing or predicted plume area.	No
		Point-of-Use Treatment	No ground water is extracted from the plume area for any use.	No
		Meetings/Newsletters	Base public relations and environmental management offices have many information avenues to workers and residents.	Yes
Containment of Plume	Hydraulic Controls	Passive Drain Collection	No likely receptors downgradient of site. Installation could disrupt base operations.	No
		Minimum Pumping/Gradient Control	A line or semicircle of vertical pumping wells could be located along the leading edge of plume to intercept and halt the advance of the plume. No likely receptors downgradient of site.	No
	Physical Controls	Slurry Walls/Grout Curtains	Requires significant disruption of base operating area. Limited effectiveness.	No
		Sheet Piling	Requires significant disruption of base operating area. Limited effectiveness.	No
	Reactive/Semi-Permeable Barriers	Biologically Active Zones	Natural biodegradation of BTEX compounds can be stimulated by allowing contaminated ground water to flow through an aquifer zone which has enhanced oxygen and nutrient conditions.	No

TABLE 6.2 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF
TECHNOLOGIES AND PROCESS OPTIONS FOR GROUND WATER REMEDIATION
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

General Response Action	Technology Type	Process Option	Implementability	Retain
In Situ Treatment	Biological	Oxygen and/or Nutrient Enhanced Biodegradation (Biosparging)	Differs from biologically active zone in that oxygen and/or nutrients are injected upgradient of plume and allowed to migrate downgradient. In theory, this method can more rapidly reduce higher BTEX concentrations in and immediately downgradient of the source area.	Yes
	Chemical/Physical	Intrinsic Remediation	A combination of natural biological, chemical, and physical removal mechanisms which occur to varying degrees on every site. Ground water sampling at Site ST-29 indicates that this is a major, ongoing remediation process.	Yes
		Air Sparging (Volatilization)	Injection of air into contaminated aquifer creating a mass transfer of BTEX into air bubbles and into vadose zone. Limited radius of influence and short-circuiting are common problems.	No
Aboveground Ground Water Treatment	Ground Water Extraction	Vertical Pumping Wells	Entire groundwater plume is pumped by installing numerous wells with submersible pumps. High cost and major disruption to area.	No
		Downgradient Horizontal Drains	See Passive Drain Collection.	No
	Biological	Bioreactors	High flow rates require excessive retention times and large reactors. BTEX is often volatilized in these systems.	No
	Chemical/Physical	Air Stripping	Cost-effective technology for removing varying concentrations of BTEX at higher flow rates. Potential permitting for air emissions.	No
		Activated Carbon	Cost prohibitive for more concentrated BTEX. Creates a carbon disposal problem.	No
		UV/Ozone Reactors	High flow rates require excessive retention times and large, expensive reactors.	No

TABLE 6.2 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF
TECHNOLOGIES AND PROCESS OPTIONS FOR GROUND WATER REMEDIATION
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

General Response Action	Technology Type	Process Option	Implementability	Retain
Aboveground Treatment	Direct Discharge to Industrial Waste Water Treatment Plant (IWWTP)		Viable option when an IWWTP is available and capable of handling BTEX and hydraulic loading.	No
Treated Ground Water Disposal	Discharge to IWWTP or Sanitary Sewer	IWWTP	Viable option when access to sanitary sewer exists and hydraulic loading is acceptable. Ground water extraction is unlikely.	No
		Sanitary Sewer	Viable option when access to sanitary sewer exists and hydraulic loading is acceptable.	No
		Vertical Injection Wells	Not recommended due to clogging and high maintenance.	No
		Injection Trenches	Require large trenches and can be subject to injection well permitting.	No
Source Removal/Soil Remediation	Treated Ground Water Reinjection	Storm Drains	Viable option but generally requires NPDES or other discharge permit. Ground water extraction is unlikely.	No
		Dual-Pump Systems	Best suited for sites with >1 foot free product where aboveground ground water treatment already exists	No
	Discharge to Surface Waters	Skimmer Pumps/Bailers/Wicks	Best suited for sites with <1 foot free product where ground water pumping is undesirable.	No
		Total Fluids Pumping	Best suited for sites with thin saturated zones where excessive ground water will not be pumped.	No
		Bioslurping	Combined vapor extraction, bioventing and free product recovery system has been operated at some sites with limited success.	No
	Excavation/ Treatment	Biological Landfarming	Excavation is not feasible at this site due to surface structures and facility use.	No

TABLE 6.2 (Concluded)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF
TECHNOLOGIES AND PROCESS OPTIONS FOR GROUND WATER REMEDIATION
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

General Response Action	Technology Type	Process Option	Implementability	Retain
	Excavation/ Treatment (cont'd)	Thermal Desorption	Excavation is not feasible at this site due to surface structures and site use.	No
	In Situ	Bioventing	Air injection to stimulate biodegradation of fuel residuals. Pilot system currently operating in source area.	Yes
		Soil Vapor Extraction	Vapor extraction has been successfully implemented at other sites. Requires expansive off-gas treatment.	Yes

Biosparging should be considered as an additional source removal mechanism. Bioventing and biosparging could easily be combined at this site by injecting air several feet below the groundwater surface and allowing air (oxygen) to move upward through the capillary fringe and into the contaminated vadose zone. This combination of two technologies using a single air injection well should be considered when designing the full-scale bioventing system. Biosparging would also increase the DO content of the groundwater and promote more rapid degradation of BTEX compounds in the plume.

Intrinsic remediation is achieved when naturally occurring attenuation mechanisms bring about a reduction in the total mass of a contaminant in the soil or dissolved in groundwater. Intrinsic remediation results from the integration of several subsurface attenuation mechanisms that are classified as either destructive or nondestructive. Destructive attenuation mechanisms include biodegradation, abiotic oxidation, and hydrolysis. Nondestructive attenuation mechanisms include sorption, dilution (caused by dispersion and infiltration), and volatilization. In some cases, intrinsic remediation will reduce dissolved contaminant concentrations below numerical concentration goals intended to be protective of human health and the environment. Based on the existing evidence of intrinsic remediation described in Section 4, these processes are occurring at Site ST-29 and will continue to reduce contaminant mass as the plume advances.

Results of model PATC suggest that if BTEX enters groundwater at a constant rate for an indefinite period of time, the dissolved BTEX plume should stabilize within approximately 30 years. This plume could extend to a maximum of 1,200 feet downgradient from the source area. This does not take into account source reduction through bioventing or weathering of the residual product trapped in the soil pores. Model PATD assumes a significant reduction in the rates of BTEX loading into the groundwater. After 7 years of source removal, the Bioplume II model predicts that the combination of source reductions and intrinsic remediation within the BTEX plume will significantly reduce its size and concentration. Under this scenario, model results show that it is unlikely that BTEX compounds would migrate more than 600 feet beyond the source area.

Implementation of Alternative 1 would require the use of institutional controls such as land use restrictions and LTM. Land use restrictions may include placing long-term restrictions on soil excavation within the source area and long-term restrictions on groundwater well installations within and downgradient of the source area. The intent of these restrictions would be to reduce potential receptor exposure to contaminants by legally restricting activities within areas affected

by site-related contamination. The two previously discussed model scenarios delineate the minimum and maximum possible plume migration distances. Future plume migration and degradation will most likely result in conditions that fall between these limits. To be conservative, the results of model PATC should be considered in making decisions regarding groundwater monitoring and potential land use restrictions.

At a minimum, groundwater monitoring would be conducted twice annually as part of this remedial technology to evaluate the progress of natural attenuation processes. Based on the potential plume migration suggested by model PATC, it is unlikely that benzene concentrations exceeding the state target cleanup goal of 11 µg/L would be present more than 1,200 feet downgradient of the source area (this would be true even if it were assumed that model contaminant concentrations are all benzene rather than total BTEX). Results of model PATD suggest that, at its maximum extent, the BTEX plume would reach no more than 600 feet beyond the source area.

Because there are no apparent downgradient receptors, POC wells should be placed downgradient from the modeled maximum extent (i.e., slightly more than 1,200 feet downgradient of the source area). In addition, LTM wells within, upgradient and immediately downgradient of the existing BTEX plume would be used to monitor the effectiveness of intrinsic remediation. LTM wells are further described in Section 7.2.1. Detection of benzene in excess of 1 µg/L at the POC wells may require additional evaluation and modeling to assess BTEX migration and to determine if any BTEX will reach the Banana River, or to determine if additional corrective action would be necessary. Land and groundwater use restrictions would also require reevaluation.

Public education on the selected alternative would be developed to inform Base personnel and residents of the scientific principles underlying source reduction and intrinsic remediation. This education could be accomplished through public meetings, presentations, press releases, and posting of signs where appropriate. Periodic site reviews also could be conducted every year using data collected from the long-term groundwater monitoring program. The purpose of these periodic reviews would be to evaluate the extent of contamination, assess contaminant migration and attenuation through time, document the effectiveness of source removal and institutional controls at the site, and reevaluate the need for additional remedial actions at the site.

6.3.2 Alternative 2 - Intrinsic Remediation and Institutional Controls with Long-Term Groundwater Monitoring

This alternative is identical to Alternative 1 except that bioventing would not continue. Rapid reduction of soil BTEX (and TPH) concentrations would not occur, and the source area would continue to contribute hydrocarbons to groundwater. Contaminant loading rates would eventually decrease, but more slowly than under Alternative 1.

As with Alternative 1, institutional controls and LTM would be required. POC wells would be installed in the same locations indicated in the previous section.

6.4 EVALUATION OF ALTERNATIVES

This section provides a comparative analysis of each of the remedial alternatives based on the effectiveness, implementability and cost criteria. A summary of this evaluation is presented in Section 6.5.

6.4.1 Alternative 1 - Continued Bioventing in Source Area, Intrinsic Remediation, and Institutional Controls with Long-Term Monitoring

6.4.1.1 Effectiveness

Section 5 of this document presents the results of the Bioplume II model completed to support the intrinsic remediation alternative at Site ST-29. The potential impacts of continued BTEX dissolution on groundwater contamination over time were incorporated into one of the models (PATC) for this remedial alternative. The other model (PATD) incorporated the effects of rapid and thorough reduction of BTEX loading rates by bioventing.

Model results predicted that natural attenuation mechanisms will significantly limit contaminant migration and reduce contaminant mass and toxicity. Benzene concentrations should not exceed the state groundwater standards/cleanup goals (Table 6.1) at the POC wells. The Bioplume II model is based upon numerous conservative assumptions and does not fully account for the anaerobic biodegradation caused by methanogenesis and other processes. In addition, it is highly unlikely that benzene concentrations in excess of 111g/L will reach the POC wells. Groundwater monitoring at the POC wells and other wells along the leading edge of the existing plume will ensure the protectiveness of this alternative. While this alternative would not cease to be protective if the benzene plume was intercepted by the POC wells, such an instance would indicate that site conditions should be reevaluated.

The effectiveness of this remedial alternative requires that excavations or drilling within the source area be conducted only by properly protected site workers. Reasonable land use assumptions for the plume area indicate that exposure is unlikely unless excavation or drilling

activities bring saturated soil to the surface. Long-term land use restrictions would be required to ensure that shallow groundwater will not be pumped or removed for potable use within, and approximately 1,000 feet in all directions from, the existing BTEX plume. Existing health and safety plans should be enforced to reduce risks from operating existing source reduction technologies and from installing and monitoring additional POC wells.

Compliance with program goals is one component of the long-term effectiveness evaluation criterion. Alternative 1 will satisfy program objectives designed to promote intrinsic remediation as a component of site remediation and to scientifically document naturally occurring processes.

Alternative 1 is based on the effectiveness of enhanced naturally occurring processes that minimize contaminant migration and reduce contaminant mass over time, and the effectiveness of institutional controls. As described earlier, an investigation of the potential effectiveness of naturally occurring processes at Site ST-29 using field data and the Bioplume II model demonstrated that the BTEX plume migration will be significantly limited. The sensitivity analysis completed on the Bioplume II model for this site (Section 5) suggests that even under the most conservative (i.e., worst-case) conditions, the naturally occurring processes at Site ST-29 should reduce contaminant migration so that the maximum distance traveled by the plume is unlikely to be beyond the proposed POC wells. The actual maximum migration distance is likely to be much less than the maximum predicted distance of 1,400 feet beyond the source area, due to the reduction of soil BTEX concentrations via bioventing.

Aside from the administrative concerns associated with long-term enforcement of long-term land use restrictions and long-term groundwater monitoring programs, this remedial alternative should provide reliable, continued protection. For cost comparison purposes, and based on Bioplume II modeling results, it is assumed that bioventing would continue for 3 years and that dissolved benzene concentrations will exceed state cleanup goals throughout the plume for approximately 7 years under Alternative 1. An additional 5 years of semiannual groundwater monitoring would be required to ensure that intrinsic remediation has uniformly reduced all BTEX compounds to concentrations below state MCLs.

6.4. 1.2 Implementability

Alternative 1 is not technically difficult to implement. Expansion of the bioventing system is planned for 1995. Installation of POC wells and semiannual groundwater monitoring are both standard procedures. Long-term management efforts would be required to ensure proper sampling procedures are followed. Periodic site reviews should be conducted to confirm the adequacy and

completeness of LTM data and verify the effectiveness of this remediation approach. There may also be administrative concerns associated with long-term enforcement of groundwater use restrictions. Future land use within the source area may be impacted by leaving contaminated soil and groundwater in place. Regulators and the public would have to be informed of the benefits and limitations of the intrinsic remediation option. Educational programs are not difficult to implement, and the initial regulatory reaction to this alternative has been positive.

6.4.1.3 Cost

The cost of Alternative 1 is summarized in Table 6.3. Capital costs are limited to the construction of three new POC wells, two new LTM wells, and four new bioventing wells. The cost of maintaining the full-scale bioventing system for 3 years is included in the \$277,000 total present worth cost estimate for Alternative 1. Also included are the costs of maintaining institutional controls and long-term groundwater monitoring for a total of 12 years.

6.4.2 Alternative 2 - Intrinsic Remediation and Institutional Controls with Long-Term Groundwater Monitoring

6.4.2.1 Effectiveness

Because of the lack of a source removal component, the effectiveness of Alternative 2 is diminished compared to Alternative 1. However, this alternative also complies with the program goals because intrinsic remediation remains the predominant decontamination method for the site. State target cleanup goals will be achieved at the POC, as described in Alternative 1.

6.4.2.2 Implementability

The installation of POC and LTM wells, the institutional controls, and the long-term monitoring commitments described in Alternative 1 would be implemented with this alternative.

6.4.2.3 Cost

The estimated capital and operating costs of Alternative 2 are shown in Table 6.4. The total present worth cost of Alternative 2 is \$226,000. The cost of Alternative 2 will be decreased from

TABLE 6.3

**ALTERNATIVE 1- COST ESTIMATE
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA**

<u>Capital Costs</u>	<u>Cost</u>
Design/Construct Three POC Wells and Two LTM Wells	\$14,000
Expand Bioventing System (4 new wells)	\$80,000
<u>Operation, Maintenance and Monitoring Costs (Annual)</u>	<u>Annual Cost</u>
Operate and Maintain Bioventing System (3 years)	\$12,000
Conduct Semiannual Groundwater Monitoring of 7 Wells (12 years)	\$6,000
Maintain Institutional Controls/Public Education (12 years)	\$5,000
Project Management (12 years)	\$6,000
<u>Present Worth of Alternative 1</u> ^{a/}	\$277,000

^{a/} Based on an annual inflation (discount) factor of 5 percent.

TABLE 6.4
ALTERNATIVE 2 - COST ESTIMATE
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AFB, FLORIDA

<u>Capital Costs</u>	<u>Cost</u>
Design/Construct Three POC Wells and Two LTM Wells	\$14,000
<u>Operation, Maintenance and Monitoring Costs (Annual)</u>	<u>Annual Cost</u>
Conduct Semiannual Groundwater Monitoring of 7 Wells (20 years)	\$6,000
Maintain Institutional Controls/Public Education (20 years)	\$5,000
Project Management (20 years)	\$6,000
<u>Present Worth of Alternative 2</u> ^{a/}	\$226,000

^{a/} Based on an annual inflation (discount) factor of 5 percent.

the costs of Alternative 1 by the omission of bioventing, but monitoring would be continued for 20 years to verify that the plume continues to degrade and does not reach the POC wells. Based on model predictions, the plume will migrate farther downgradient than under Alternative 1, but it should not move more than 1,200 feet beyond the source area once it stabilizes. Annual long term monitoring would continue for 20 years to ensure that intrinsic remediation is reducing BTEX concentrations below state cleanup goals throughout the plume. A monitoring period of 20 years was selected to allow sufficient time for weathering and degradation of residual LNAPL in the source area to reduce the introduction of dissolved BTEX into the shallow groundwater.

6.5 RECOMMENDED REMEDIAL APPROACH

Two remedial alternatives have been evaluated for remediation of the shallow groundwater at Site ST-29. Components of the alternatives evaluated include bioventing/biosparging, intrinsic remediation with LTM, and institutional controls. Table 6.5 summarizes the results of the evaluation based upon effectiveness, implementability, and cost criteria. Based on this evaluation, the Air Force recommends Alternative 1 as achieving the best combination of risk reduction and cost effectiveness.

A bioventing system is already operating, and the benefits of expanding and continuing the source reduction for 3 years should offset the additional capital and operating costs. Based on all effectiveness criteria, Alternative 1 will make maximum use of intrinsic remediation mechanisms to reduce plume migration and toxicity while providing the added benefits of enhanced in situ soil remediation in the source area and the introduction of additional oxygen into the groundwater in the vicinity of the bioventing well.

Both of the remedial alternatives are implementable; however, Alternative 1 more effectively reduces potential hydrocarbon migration and toxicity. This alternative should be acceptable to the public and regulatory agencies because it is protective of human health and the environment and reduces soil and groundwater contamination in a shorter time frame. Implementation of Alternative 1 will require land use and groundwater use controls to be enforced for approximately 12 years, along with semi-annual groundwater monitoring for the same period.

The final evaluation criterion used to compare each of the two remedial alternatives was cost. It is the opinion of the Air Force that the additional cost of Alternative 1 over Alternative 2 is justified by the additional protection it provides and the reduction in treatment time.

TABLE 6.5

SUMMARY OF REMEDIAL ALTERNATIVES EVALUATION
GROUND WATER REMEDIATION
SITE ST-29 INTRINSIC REMEDIATION EE/CA
PATRICK AFB, FLORIDA

Remedial Alternative	Effectiveness	Implementability	Present Worth Cost Estimate
Alternative 1 - Continued (Expanded) Bioventing - Intrinsic Remediation - Long-Term Monitoring	Continued bioventing will gradually remove BTEX source. Contaminant mass, volume and toxicity will be significantly reduced over next seven years. MCL for benzene not likely to be exceeded at POC.	Readily implementable. Long-term management, ground water use controls and monitoring required for an estimated 12 years. Minimal exposure of site workers if excavation is carefully controlled in source area.	\$277,000
Alternative 2 - Intrinsic Remediation - Long-Term Monitoring	Similar to Alternative 1, with the omission of bioventing. Contaminant mass, volume, and toxicity will be reduced, but more slowly than in Alternative 1. Potential for MCLs to be exceeded at POC.	Readily implementable. Long-term management, ground water controls, and monitoring required for an estimated 20 years. If MCLs exceeded at POC, additional remedial work may be required.	\$226,000

SECTION 7

LONG-TERM MONITORING PLAN

7.1 OVERVIEW

In keeping with the requirements of the preferred remedial alternative for Site ST-29 (continued bioventing and intrinsic remediation with LTM), a long-term groundwater monitoring plan must be developed. The purpose of this component of the preferred remedial alternative for Site ST-29 is to assess site conditions over time, confirm the effectiveness of bioventing and naturally occurring processes at reducing contaminant mass and minimizing contaminant migration, and evaluate the need for additional remediation. The results of LTM can be used to validate model predictions and assure compliance with regulatory standards at the POC. If it is shown that the model does not accurately represent BTEX migration and attenuation at the ST-29 site, the model can be refined and recalibrated, as necessary.

To demonstrate attainment with both levels of site-specific remediation goals and to verify the accuracy of the Bioplume II model developed for Site ST-29, the LTM plan consists of identifying the location of two separate groundwater monitoring networks and developing a groundwater sampling and analysis strategy. The strategy described in this section is designed to monitor plume migration over time and to verify that intrinsic remediation is occurring at rates sufficient to protect potential receptors. In the event that data collected under this long-term program indicate that naturally occurring processes are insufficient to protect human health and the environment, this plan also describes contingency controls to augment the beneficial effects of intrinsic remediation.

As noted in Section 1.1, the scope of this project focuses on the intrinsic remediation of BTEX compounds; therefore, the plans specified in this section are geared toward monitoring for those specific target compounds. Clearly, any comprehensive monitoring program for this site also will need to include analyses specified in Chapter 62-770, FAC to meet the other target cleanup goals listed in Table 6.1.

7.2 MONITORING NETWORKS

Two separate sets of wells will be installed at Site ST-29 as part of the intrinsic remediation remedial alternative. The first set will consist of four wells located in, upgradient, and downgradient of the observed BTEX plume to verify the results of the Bioplume II modeling effort and to ensure that natural attenuation is occurring at rates sufficient to minimize plume expansion (i.e., meet the first level of remediation concentration goals for the site). This network of wells will consist of existing and proposed wells screened within the shallow aquifer to provide short-term confirmation and verification of the quantitative groundwater modeling results. The second set of groundwater monitoring wells will be located along a line slightly more than 1,200 feet downgradient from the source area (the POC for this demonstration project). The purpose of the POC wells is to verify that no BTEX compounds exceeding their state groundwater standards migrate beyond the area under institutional control (i.e., meet the second level of remediation concentration goals for the site). This network will consist of three groundwater monitoring wells screened across the first 10 feet of the shallow aquifer. Both LTM and POC wells will be sampled for analysis of the parameters listed in Tables 7.1 and 7.2, respectively.

7.2.1 Long-Term Monitoring Wells

At six locations, groundwater wells within, upgradient, and downgradient from the existing BTEX contaminant plume will be used to monitor the effectiveness of intrinsic remediation in reducing total contaminant mass and minimizing contaminant migration. Three locations will be within the anaerobic treatment zone. New monitoring wells at two downgradient locations will be placed beyond the aerobic treatment zone downgradient of the existing BTEX plume. In addition, one well upgradient of the existing plume will be monitored.

At four of the locations, existing monitoring wells/points will be used for this purpose. Well PB-5/MW-11 will be used to monitor conditions upgradient of the plume, while monitoring points CPT-03, CPT-14, and CPT-18 will be used to monitor conditions in the anaerobic treatment zone. For monitoring downgradient from the anaerobic treatment zone, wells should be installed at two new locations. Figure 7.1 identifies the proposed locations of each of these wells. This network will supplement the POC wells to provide early confirmation of model predictions and to allow additional response time if necessary. New

TABLE 7.1
LONG-TERM MONITORING ANALYTICAL PROTOCOL
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AIR FORCE BASE, FLORIDA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Ferrous Iron (Fe ²⁺)	Colorimetric A3500-Fe D	Field only	Elevated ferrous iron concentrations may be indicative of the anaerobic biodegradation process of iron reduction	Semiannually for 12 Years	Collect 100 mL of water in a glass container; acidify with hydrochloric acid per method	Field
Ferrous Iron (Fe ²⁺)	Colorimetric HACH 25140-25	Alternate method; field only	Same as above.	Semiannually for 12 Years	Collect 100 mL of water in a glass container	Field
Temperature	E170.1	Field only	Metabolism rates for microorganisms depend on temperature	Semiannually for 12 Years	N/A	Field
Dissolved Oxygen	Dissolved oxygen meter	Refer to Method A4500 for a comparable laboratory procedure	The oxygen concentration is an indicator of biodegradation conditions; concentrations less than 1 mg/L generally indicate an anaerobic pathway	Semiannually for 12 Years	Collect 300 mL of water in biochemical oxygen demand bottles; analyze immediately; alternately, measure dissolved oxygen in situ	Field
pH	E150.1/SW9040, direct reading meter	Protocol/Handbook methods ^d	Aerobic and anaerobic processes are pH-sensitive	Semiannually for 12 Years	Collect 100–250 mL of water in a glass or plastic container; analyze immediately	Field
Conductivity	E120.1/SW9050, direct reading meter	Protocol/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system	Semiannually for 12 Years	Collect 100–250 mL of water in a glass or plastic container	Field
Nitrate (NO ₃ ⁻¹)	IC method E300 or method SW9056; colorimetric, method E353.2	Method E300 is a Handbook method; method SW9056 is an equivalent procedure	Substrate for microbial respiration if oxygen is depleted	Semiannually for 12 Years	Collect up to 40 mL of water in a glass or plastic container; cool to 4°C; analyze within 48 hours	Fixed-base

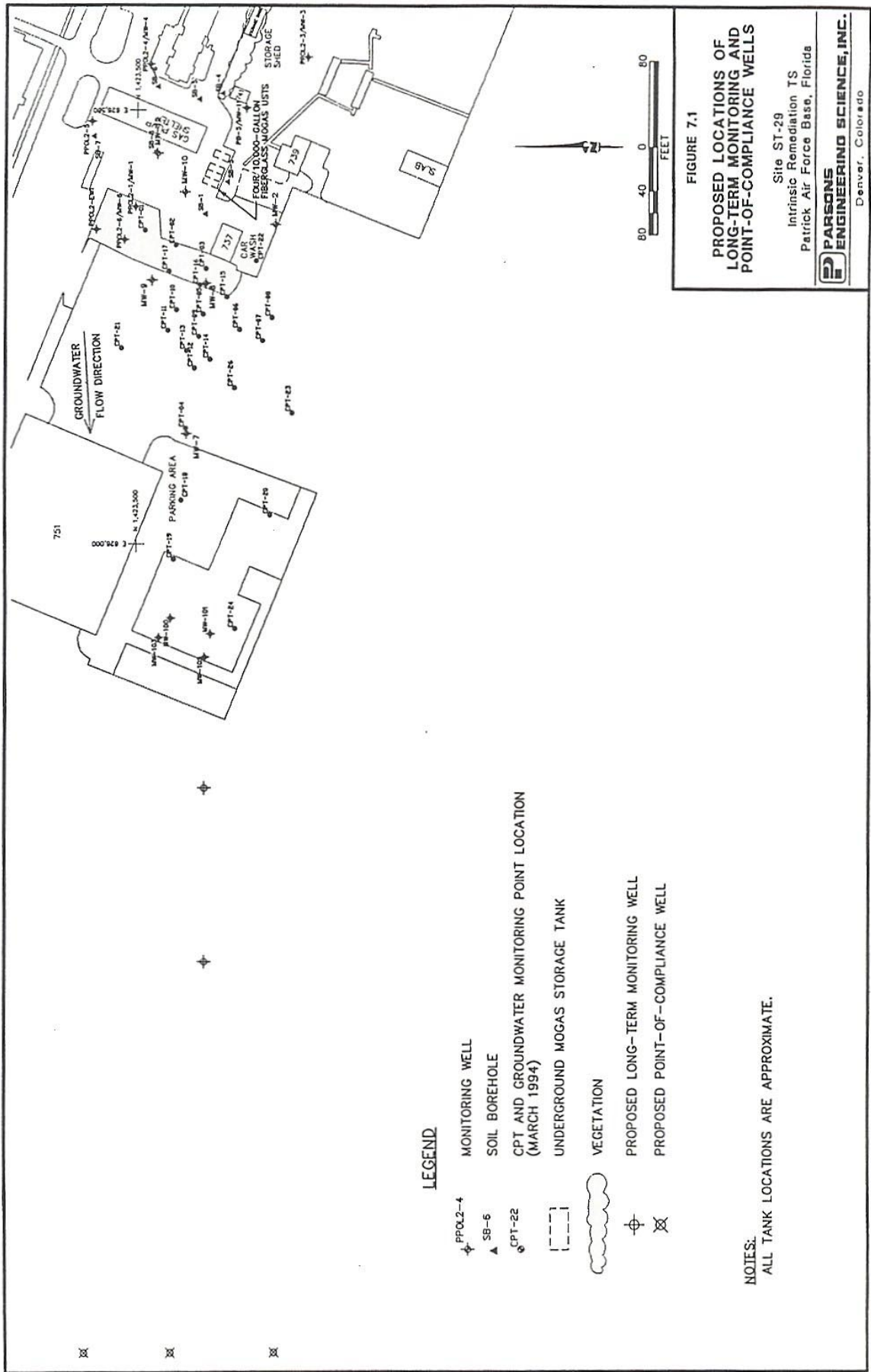
TABLE 7.1 (CONCLUDED)
LONG-TERM MONITORING ANALYTICAL PROTOCOL
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AIR FORCE BASE, FLORIDA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Sulfate (SO_4^{2-})	IC method E300 or method SW9056 or HACH SulfVer 4 method	Method E300 is a Handbook method; method SW9056 is an equivalent procedure. HACH method is Photometric	Substrate for anaerobic microbial respiration	Semiannually for 12 Years	Collect up to 40 mL of water in a glass or plastic container; cool to 4°C	Fixed-base or field (for HACH method)
Redox potential	A2580 B	Measurements are made with electrodes; results are displayed on a meter, samples should be protected from exposure to atmospheric oxygen	The redox potential of groundwater influences and is influenced by biologically mediated reactions; the redox potential of groundwater may range from more than 200 mV to less than -400 mV	Semiannually for 12 Years	Collect 100–250 mL of water in a glass container, filling container from bottom; analyze immediately	Field
Methane, Ethane, and Ethene	RSKSOP-114 modified to analyze water samples for methane by headspace sampling with dual thermal conductivity and flame ionization detection.	Method published and used by the USEPA Robert S. Kerr Laboratory	The presence of methane suggests BTEX degradation via an anaerobic pathway utilizing carbon dioxide (carbonate) as the electron acceptor (methanogenesis). The presence of ethane and ethene suggest that cometabolism of vinyl chloride is occurring.	Semiannually for 12 Years	Collect water samples in 40 mL volatile organic analysis (VOA) vials with butyl gray/Teflon-lined caps (zero headspace); cool to 4°C	Fixed-base
Aromatic hydrocarbons (BTEX)	Purge and trap GC method SW8020.	Handbook method; analysis may be extended to higher molecular weight alkylbenzenes	BTEX is the primary target analyte for monitoring natural attenuation; BTEX concentrations must also be measured for regulatory compliance	Semiannually for 12 Years	Collect water samples in a 40 mL VOA vial with zero headspace; cool to 4°C; add hydrochloric acid to pH ≤ 2	Fixed-base

TABLE 7.2
POINT-OF-COMPLIANCE MONITORING ANALYTICAL PROTOCOL
SITE ST-29 INTRINSIC REMEDIATION TS
PATRICK AIR FORCE BASE, FLORIDA

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Temperature	E170.1	Field only	Well development	Semiannually for 12 Years	N/A	Field
Dissolved Oxygen	Dissolved oxygen meter	Refer to method A4500 for a comparable laboratory procedure	The oxygen concentration is an indicator of biodegradation conditions; concentrations less than 1 mg/L generally indicate an anaerobic pathway	Semiannually for 12 Years	Collect 300 mL of water in biochemical oxygen demand bottles; analyze immediately; alternately, measure dissolved oxygen in situ	Field
pH	E150.1/SW9040, direct reading meter	Protocols/Handbook methods ^a	Aerobic and anaerobic processes are pH-sensitive	Semiannually for 12 Years	Collect 100–250 mL of water in a glass or plastic container; analyze immediately	Field
Conductivity	E120.1/SW9050, direct reading meter	Protocols/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system	Semiannually for 12 Years	Collect 100–250 mL of water in a glass or plastic container	Field
Redox potential	A2580 B	Measurements are made with electrodes; results are displayed on a meter; samples should be protected from exposure to atmospheric oxygen	The redox potential of groundwater influences and is influenced by biologically mediated reactions; the redox potential of groundwater may range from more than 200 mV to less than -400 mV	Semiannually for 12 Years	Collect 100–250 mL of water in a glass container, filling container from bottom; analyze immediately	Field
Lead	SW7421 or 239.2	Standard methods	Lead must be measured for regulatory compliance	Semiannually for 12 Years	Collect 100–250 mL of water in a glass or plastic container; add nitric acid to pH ≤ 2	Fixed-base
1,2-dichloroethane and EDB	Purge and trap GC method SW8010	Handbook method	Halogenated hydrocarbon concentrations must be measured for regulatory compliance	Semiannually for 12 Years	Collect water samples in a 40 mL VOA vial with zero headspace; cool to 4°C; add hydrochloric acid to pH ≤ 2	Fixed-base
Aromatic hydrocarbons (BTX), plus MTBE	Purge and trap GC method SW8020	Handbook method; analysis may be extended to higher molecular weight alkylbenzenes	BTX are the primary target analytes for monitoring natural attenuation; BTX and MTBE concentrations must also be measured for regulatory compliance	Semiannually for 12 Years	Collect water samples in a 40 mL VOA vial with zero headspace; cool to 4°C; add hydrochloric acid to pH ≤ 2	Fixed-base

^a Protocol methods are presented by Wiedemeier *et al.* (1995).



LTM wells will be constructed with 10-foot screens with approximately 8 feet of the screen below the water table. These wells will be sampled and analyzed for the parameters listed in Table 7.1 to verify the effectiveness of the intrinsic remediation remedial alternative.

7.2.2 Point-of-Compliance Wells

Three POC monitoring wells will be installed approximately 800 feet downgradient of the existing BTEX plume. Figure 7.1 also identifies the proposed locations of these wells. The purpose of these POC wells is to verify that no contaminated groundwater exceeding the state cleanup standards listed in Table 6.1 migrates beyond the area under institutional control. Although model results suggest that the contaminant plume will not migrate to or beyond this location at concentrations exceeding chemical-specific state standards, these POC wells are the technical mechanisms used to demonstrate protection of human health and the environment and compliance with site-specific numerical remediation goals. These wells will be installed and monitored for the parameters listed in Table 7.2 to assure that the selected remedy is providing the anticipated level of risk reduction and remediation at the site.

As with the LTM wells, the POC wells also will be screened in the same hydrogeologic unit as the contaminant plume. Data presented in this report about the nature and extent of contamination at the site suggest that a 10-foot screen extending from slightly above the surface of the groundwater to the shallow confining unit will be sufficient to intercept the contaminant plume at this site. Figure 7.2 is a proposed groundwater monitoring well completion diagram for both the LTM wells and the POC wells.

7.3 GROUNDWATER SAMPLING

To ensure that sufficient contaminant removal is occurring at Site ST-29 to protect human health and the environment and meet site-specific remediation goals, the long-term groundwater monitoring plan includes a comprehensive SAP. All LTM and POC wells will be sampled and analyzed twice each year to verify that naturally occurring processes are effectively reducing contaminant mass and mobility. Reductions in toxicity will be implied by mass reduction. The SAP will also be aimed at assuring intrinsic remediation can achieve site-specific remediation concentration goals for BTEX compounds and protect human health and the environment.

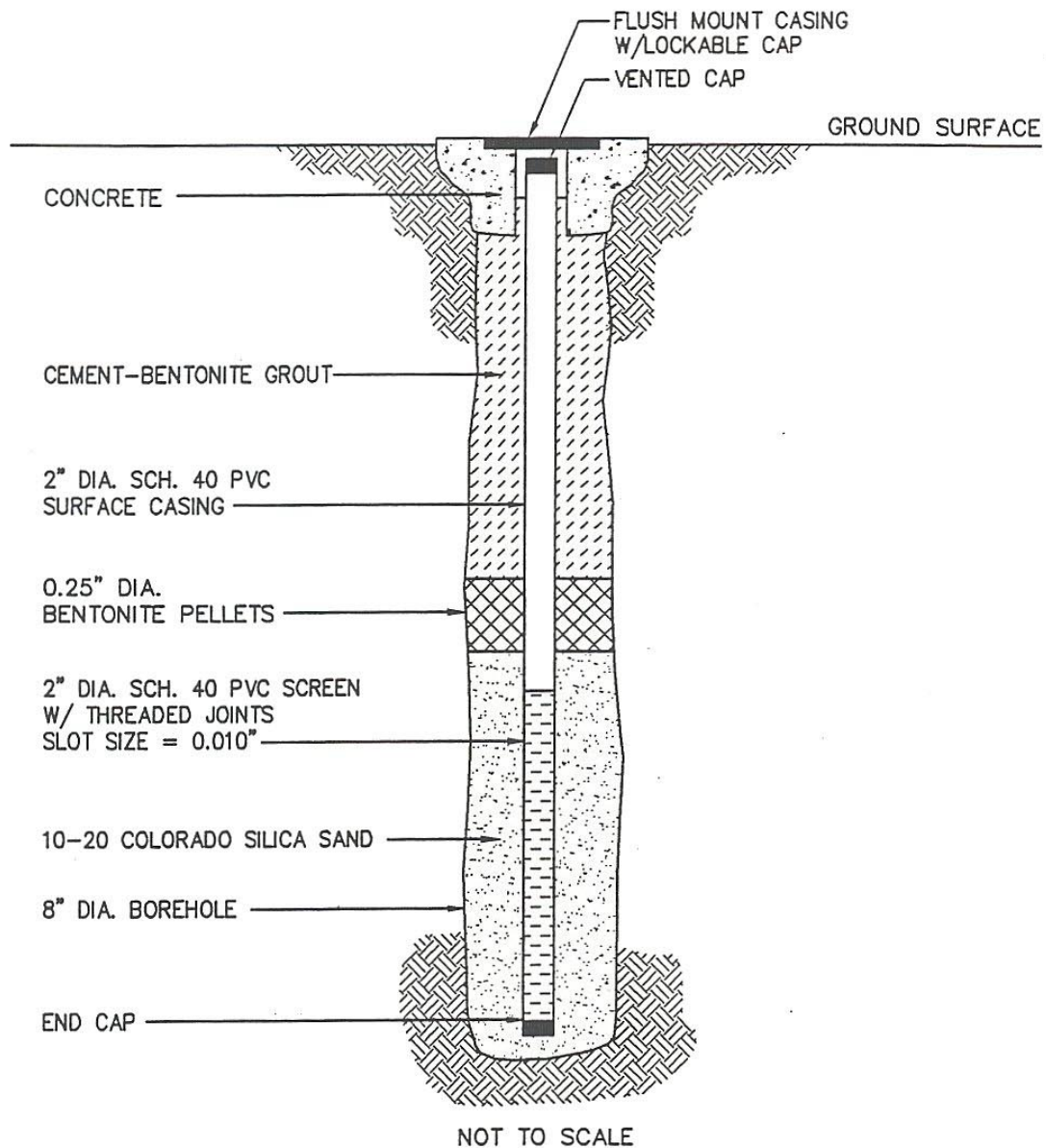


FIGURE 7.2

**PROPOSED MONITORING WELL
COMPLETION DIAGRAM**

Site ST-29
Intrinsic Remediation TS
Patrick Air Force Base, Florida



**PARSONS
ENGINEERING SCIENCE, INC.**

Denver, Colorado

7.3.1 Analytical Protocol

All LTM and POC wells in the LTM program will be sampled and analyzed to determine compliance with chemical-specific remediation goals (Table 6.1) and to verify the effectiveness of intrinsic remediation at the site. Water level measurements will be made during each sampling event. All groundwater samples will be analyzed for the parameters listed in Tables 7.1 and 7.2. A site-specific groundwater SAP should be prepared as part of the RAP prior to initiating the LTM program.

7.3.2 Sampling Frequency

Each of the LTM and POC sampling points will be sampled twice each year for 12 years. If the data collected during this time period supports the anticipated effectiveness of the intrinsic remediation alternative at this site, the sampling frequency can be reduced to once every year for all wells in the LTM program, or eliminated. If the data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, sampling frequency should be adjusted accordingly.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

This report presents the results of a TS conducted to evaluate the use of intrinsic remediation (natural attenuation) for remediation of fuel-hydrocarbon-contaminated groundwater at the BX Service Station (Site ST-29), Patrick AFB, Florida. Specifically, the finite-difference groundwater model Bioplume II was used in conjunction with site-specific geologic, hydrologic, and laboratory analytical data to simulate the migration and oxygen limited biodegradation of fuel hydrocarbon compounds dissolved in groundwater. Groundwater contaminant and geochemical data strongly suggest that aerobic biodegradation of fuel hydrocarbons is occurring at the site. In addition, the data also suggest that anaerobic biodegradation is occurring via methanogenesis and, to a lesser degree, iron reduction.

To collect the data necessary for the intrinsic remediation demonstration, Parsons ES and USEPA researchers collected soil and groundwater samples from the site. Physical and chemical data collected under this program were supplemented with data collected during previous site characterization events. Site-specific geologic, hydrologic, and laboratory analytical data were then used in the Bioplume II numerical groundwater model to simulate the effects of advection, dispersion, sorption, and biodegradation on the fate and transport of the dissolved BTEX plume. Extensive site-specific data were used for model implementation. Model parameters that could not be obtained from existing site data were estimated using widely accepted literature values for sediments similar to those found at the site. Conservative aquifer parameters were used to construct the Bioplume II model for this study, and therefore, the model results presented herein represent conservative scenarios. It was also assumed that only aerobic biodegradation would occur.

For one simulation (model PATC), it was assumed that BTEX compounds will enter the aquifer at a constant rate. That rate was the same rate used to produce the initial calibrated model. Therefore, the results presented for PATC represent a worst-case scenario in which the BTEX plume equilibrates after about 30 years, with the leading edge of the plume stabilizing approximately 1,400 feet beyond the source area. For a second simulation (model

PATD), it was assumed that BTEX loading rates were significantly decreased by bioventing over a 3-year period. Results for PATD represent a reasonable, but still conservative scenario in which dissolved BTEX compounds would degrade to below detectable concentrations in 7 years.

Actual dissolved BTEX degradation rates observed during LTM at the site will probably be greater than predicted by model PATC and less than predicted by model PATD. This will result in faster removal rates of the BTEX compounds and a shorter plume migration distance than predicted by model PATC. In addition, bioventing should increase the diffusion of oxygen into groundwater across the soil gas-water interface. Increased diffusion causes increased ground-water reaeration, which further enhances biodegradation of dissolved petroleum hydrocarbons (Barr, 1993). Additional oxygen introduced into the subsurface by bioventing should further enhance biodegradation through oxygen diffusion across the water table, resulting in more rapid plume attenuation.

The results of this study suggest that natural attenuation of BTEX compounds is occurring at Site ST-29 to the extent that the concentrations of these compounds dissolved in groundwater should be reduced to concentrations below current regulatory guidelines long before potential downgradient receptors could be adversely affected (i.e., the potential contaminant migration pathway will not be complete for any of the potential receptors described in Section 6.2). Based on the distance to potential downgradient receptors (at least 2,500 feet to the Banana River) and rates of BTEX plume migration and degradation predicted by models PATC and PATD, the Air Force is recommending continued bioventing coupled with natural attenuation, institutional controls, and LTM as the remedial option for BTEX-impacted groundwater near Site ST-29. Construction activities and groundwater use in and downgradient from the source area should be restricted for a period of approximately 12 years.

To verify the results of the Bioplume II modeling effort, and to ensure that natural attenuation is occurring at rates sufficient to protect potential downgradient receptors, groundwater from existing monitoring well PB-5/MW-II, from existing monitoring points CPT-03, CPT-14, and CPT-18, and from two proposed LTM wells should be sampled semiannually and analyzed for the parameters listed in Tables 7.1 and 7.2. In addition, three POC groundwater monitoring wells should be installed downgradient from the predicted maximum travel distance of the BTEX plume. Figure 7.1 shows suggested locations for the three new POC monitoring wells and the two

new LTM wells. These wells should be sampled semiannually for 12 years, and the samples should be analyzed for the parameters listed in Tables 7.1 and 7.2. If dissolved BTEX concentrations in groundwater in the POC wells are found to exceed the Florida regulatory standards of 1 µg/L for benzene, 50 µg/L for total BTEX 3 µg/L for 1,2-dichloroethane, 0.02 µg/L for 1,2-dibromoethane, 50 µg/L for lead, and 50µg/L for methyl tert-butyl ether, additional evaluation or corrective action may be necessary at this site. A site-specific RAP, SAP, and quality assurance project plan (QAPP), should be submitted to the Florida Department of Environmental Protection for approval prior to implementation of the recommended remedial alternative for Site ST-29.

SECTION 9

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